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SMOKE CONTROL USING THE "CABIN PRINCIPLE": PROS AND CONS OF SHEVS AND OF DEPRESSURISATION

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ABSTRACT

Many large modern buildings, most typically airport terminals, have many well-separated retail units within a much larger space. The Cabin Principle has been used in several airport terminals and elsewhere, to contain any fire smoke in the unit on fire, thus removing the need for major fire precautions in the main space where that space has little potential fuel.

The usual application of this principle is similar to the long-established technique of the large-scale experimental calorimeter. This application has the retail unit forming an open-fronted, and/or open-sided box, and uses the methods of smoke and heat exhaust ventilation (SHEVS) to contain smoky gases within a smoke reservoir formed in that box. This approach is described in this paper as the "SHEVS Cabin" principle. Calculation procedures are described, based on existing practice for SHEVS, and an example is presented. Advantages and disadvantages of the technique are discussed. The following conclusions are reached:

- For the example cited, the optimum fan capacity is about 11.3 m^3s^{-1}.
- The successful operation of sprinklers in the cabin is essential.
- The design is not tolerant of failure in any of the equipment.
- Even in a successful design some smoke will leak past the edges of automatic drop curtains into the space outside the cabin. Whether this creates a hazardous condition or not depends on the volume of that space and the role and performance in emergency of any HVAC system in that space.
- Curtain deflection is trivial and can be ignored for the case of the cabin dimensions used in the example. Note that this conclusion cannot automatically be generalised to apply to other examples.
- The operation of sprinklers may cause some smoke to spill beneath the curtains unless the curtains can be made deeper - although this cannot be calculated. This could in some circumstances make the curtains close to or below head height for some people who might have to escape below it.
- The curtain material should be able to withstand flame temperatures. This is a more rigorous specification than is usual for most applications of smoke curtains.
- Fire safety management provisions to ensure continuing function of all equipment is essential.
- Fire safety management must include a "policing" role to prevent potential fuels being placed outside the cabin.

A novel alternative principle is developed based on closure of the front of the retail unit's "box" using an automatic drop curtain, combined with a controlled reduction of pressure within that box to prevent any leakage of smoke from the unit into the large space outside. Calculation methods for this "Depressurised Cabin" principle are presented, and a worked example is used to allow direct comparison with the SHEVS approach. The conclusions reached are:

- The cabin should have fire-resisting walls and ceiling.
- The drop curtain at the front opening should have a bottom bar which moves freely in vertical tracks fastened to the side walls of the cabin.
- This curtain should be able to withstand flame temperature gases of at least 1000 ^oC.
- The curtain must be full height, with its bottom bar resting on the floor.
- The curtain should be longer than the vertical height to the floor, with a fabric length calculated to be sufficient to prevent the bottom bar lifting.
- The weight of the bottom bar should be specified as part of a design trade-off with the overall fabric length, in order to optimise intrusion of the curtain into the retail space. For the example cited a bottom-bar weight of 10 kgm^{-1} appears suitable.
- A relatively small exhaust fan, of 1.75 m^3s^{-1} for the example's dimensions of cabin, should be used to achieve the reduction of pressure in the cabin.

- The cabin should have a barometric damper set to open at 60 Pa. For the example cited the damper should have a minimum aerodynamic free area of 0.18 m^2.
- There must be an escape door (or more than one if required by local Means of Escape rules) from the cabin for people to escape after the curtain has operated. This door should be identified by appropriate signage.
- The system is tolerant of failure of all components except the smoke curtain, which must work properly. This implies that the management of the Terminal Building must include regular, frequent, functional tests of the curtain during normal use.
- As in the case of the SHEVS cabin, the fire safety management should include a "policing" role to prevent potential fuels being placed outside the line of the smoke curtain, and also to ensure that the fall of the curtain is not blocked.

It is noted from the example calculated that the exhaust fan capacity required for depressurising can be an order of magnitude smaller than for the SHEVS Cabin approach.

1. GENERAL INTRODUCTION

1.1 The Need for Controlling Smoke from Fires in Retail Units

There is a current trend in the design of transport terminals to create a very large volume beneath the roof accessible to the travelling public. Examples include London Stansted in the UK, Kansai in Japan, and Chep Lap Kok in Hong Kong, with the early development of this approach to fire safety engineering being done by Ove Arup and Partners [1]. The trend can be expected to spread to other types of building. Fire safety in such buildings can be achieved by a combination of measures. Within the main space fuel materials must either be controlled in terms of quantity, of ignitability, or by containment. In most such buildings the largest fires which might occur will be in a retail shop unit. Potential fuels within the main space must be controlled so that no hazard is presented to the occupants, and it is of course necessary to demonstrate by calculation that the largest amount of uncontrollable fuels present (for example the carry-on baggage in an airport terminal) cannot create any threat to the occupants. It is not the purpose of the present paper to discuss methods by which this might be achieved.

It will usually be possible to assess the time required for safe evacuation of occupants of the building using an evacuation model (e.g. the Fire Research Station's model CRISP). It is not the purpose of the present paper to discuss such models, or the mixture of detection and alerting systems which might be required. It is important, however, that the smoke control methods adopted must be capable of maintaining a smoke-free environment for people throughout the evacuation process; and should provide optimum conditions for fire-fighters while they control and extinguish the fire.

In many large-volume buildings the largest amount of essentially uncontrollable fuel materials will be the sale goods and interior fittings of retail units – many of which will take the form of isolated units well separated from each other. Note that where retail units cluster in large numbers it will usually be more appropriate to design smoke control systems following guidance for shopping malls [2,3,4]. The present paper is concerned with the isolated shop unit within the large volume space. It is the purpose of this present paper to consider the options for ensuring that a fire in an isolated retail shop unit does not allow any smoke to enter the main space; and that by so containing the smoke we can ensure that people will remain free to use the Means of Escape in that space.

It is conventional in many countries to adopt a 5 MW (convective heat flow) 3 metre x 3 metre steady-state design fire for smoke control calculations where the fire is in a retail unit: provided that the unit is equipped with Standard Response sprinklers [3,4]. More recently an alternative has been recognised [4] where Quick Response sprinklers are fitted, namely a 2.5 MW (convective heat flow) fire 2.2 metres x 2.2 metres: as for example in the European Parliament Building in Brussels [5], and in many UK Shopping Malls [6].

An alternative approach to specifying a design fire is to calculate the size of fire at the moment of operation of the first sprinkler, and to assume that the fire will grow no larger [1,7]. This approach can be controversial, and may be less conservative than adopting a steady-state design fire method based ultimately on statistical arguments [8]. The steady-state approach will be adopted in this present paper. See also the discussion in 2.3 below.

1.2 Retail "Cabins"

Where retail units occur in close proximity one to another facing onto a common pedestrian area, and where that area's ceiling is not too high, smoke from a fire in a retail unit can be controlled by designing a SHEVS for that common area. This has been the approach for Shopping Malls for many years [2,3,9]. Where this cannot be done, or where the units occur singly in a well-separated way, other methods have to be adopted.

One method which has become known as "the Cabin Principle" has been adopted in London Stansted Airport, Kansai Airport (Japan), and Chep Lap Kok Airport in Hong Kong [1]. This name and usage was originated by Ove Arup & Partners Ltd. Their approach uses a Smoke and Heat Exhaust Ventilation System combined with fixed or automatically dropping smoke barriers at the open frontages of the retail unit to prevent any spillage from that unit. In this the approach is essentially similar to the "Large Store" option recommended for use with Shopping Malls [3,10], the major difference being that the Cabin Principle is primarily applied to small retail units. The concept is also similar to the large and small experimental calorimeters in widespread use in many laboratories [11]. For the purposes of the present report this approach will be re-named as "the SHEVS Cabin", and is described in Section 2 below. Note that there are disadvantages as well as advantages to this method, which are also discussed in Section 2.

An alternative approach, which may be more appropriate in many circumstances, is possible by bringing together several techniques, each of which has been developed for other circumstances, in a new way. For the purpose of the present report this can be called "the Depressurised Cabin" principle. This is discussed in Section 3 below, and design formulae are developed.

2. THE SHEVS CABIN

2.1 Principle

This is illustrated in Fig. 1. The retail unit, despite its relatively small size, has a SHEVS fully designed just for itself. The walls and ceiling (and floor) of the unit must be fire-resisting to an appropriate specification. There must be a downstand at the open front of the shop deep enough to contain the buoyant smoke layer which forms under the ceiling. This can be a permanent feature of the frontage, or it can be an automatic drop curtain deploying on receipt of a signal from a smoke detector in the unit. The latter is more common, as most "cabin" units do not have a very high ceiling and the maximum available height of opening is used to lend a more spacious impression under non-fire conditions. An exhaust system, usually using fans, must remove hot gases from the ceiling reservoir fast enough to prevent the buoyant smoke layer from becoming deeper than the downstand curtain. Replacement air enters beneath the downstand at the open front, and any people inside the unit are able to escape beneath the same downstand. Experimental test rigs based on these same principles have been used by Laboratories for many years to collect the gases from burning items (e.g. furniture [11]), or from arrays of items (e.g. displays of retail goods [12]) for analysis. Such rigs are known generically as calorimeters.

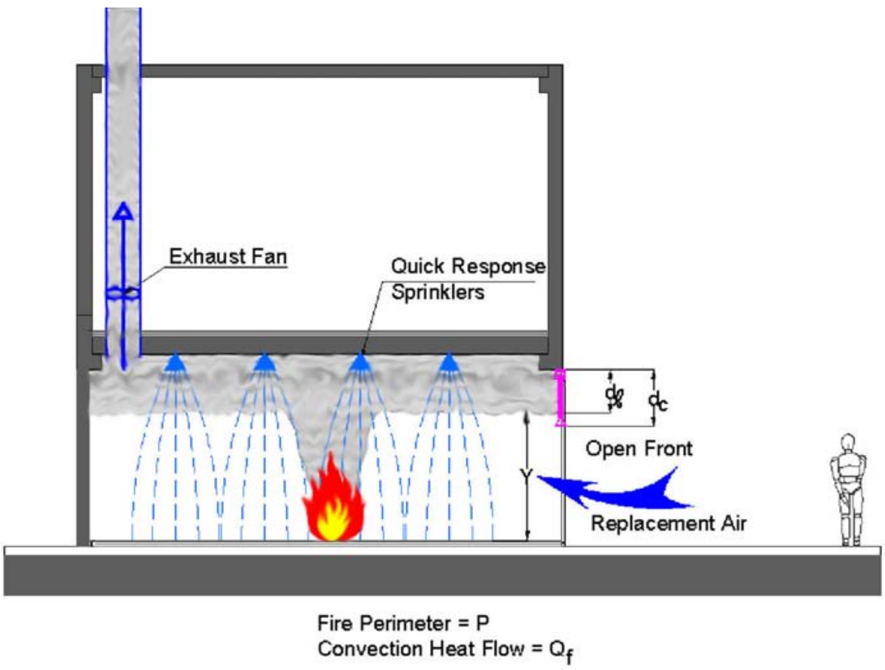

Fig. 1: The SHEVS Cabin-Principle – section through cabin

2.2 The Need for Sprinklers

First let us consider how large the fire can become without sprinklers. There are many methods for doing this, with the methods used in the present paper being outlined in Appendix 1. Results for a typical retail unit (typical of those which might be found in the "Airside" regions of an airport terminal, and used as the basis for all the calculated examples throughout the present paper) are shown in Tables 1 and 2 for units having different internal ceiling heights. The implication of these results is that as soon as an unsprinklered fire reaches 2.7 MW or 1.9 MW respectively, the fire will then grow extremely quickly to involve everything inside the unit that will burn. If we follow common practice and assume that the convective heat flux per square metre could be up to 500 kW, and for an unit plan area of 84 m^2, we could expect the fire to "jump" in size to a value which could be as large as 42 MW once flashover occurs.

Table 1: Fire size at onset of flashover, no suspended ceiling in unit

Parameter	Value
Cabin height (internal)	3.0 m
Cabin Width	10.8 m
Cabin Depth	7.8 m
Opening Height	2.6 m
Opening Width	10.8 m
Fire Size at onset of flashover	2 700 kW

Table 2: Fire size at onset of flashover, with continuous suspended ceiling in unit

Parameter	Value
Cabin height (internal)	2.6 m
Cabin Width	10.8 m
Cabin Depth	7.8 m
Opening Height	2.6 m
Opening Width	10.8 m
Fire Size at onset of flashover	1 900 kW

The practical conclusion from this is that sprinklers are essential, and any failure of the sprinklers to work would result in a much larger fire inside the cabin; greater entrainment of air into the smoke; and significant spillage of potentially large quantities of smoke into the space outside the cabin. It can be noted that Beever [1] considered the possible consequences of a sprinkler failure in the cabin or over an isolated group of fuel materials, by identifying the horizontal separation required to prevent radiative ignition of neighbouring groups of fuel. She did not, however, examine the consequences of a cabin fire exceeding the design size due to sprinkler failure, in terms of smoke spillage into the space outside the cabin.

For the purpose of the present paper, it is sufficient to note that any such large spillage of smoke is highly undesirable, and defeats the purpose of the SHEVS cabin. We can note here that, although the cabin concept was developed mainly for airport terminal buildings, it has also been used for railway terminal buildings (e.g. in Hong Kong) and is potentially useful for many other applications. This means that one cannot simply assume that the volume of the space outside the cabin will always be large, or that the ceiling of that space will always be high.

2.3 Design Parameters for a Representative Example of a SHEVS Cabin

The design process for the SHEVS cabin can follow one of several different design procedures, but for the present paper the design procedure will be that detailed in BR 368 [4], (which is similar to its predecessor BR 258 [13]), for a fire occurring below the final smoke reservoir. It is necessary to specify a design fire, as for any other SHEVS design. This has varied in past designs and has sometimes been controversial. For this example we can assume that Quick Response sprinklers have been used and that as a consequence we can adopt a 2.5 MW design fire, 2.2 m x 2.2 m in plan.

An alternative but controversial assumption is often made that the fire will never grow larger than the size which will trigger the first sprinkler [14]. Ghosh (Fire Research Station, UK), analysed the UK Fire Statistics Data Base to relate the fire-damaged area to the proportion of reported fires in public areas of retail premises. While this work has not been published, the key results were included in a paper by Morgan [15]. This showed that a small but significant proportion (7%) of fires occurring in premises where sprinklers were present, grew to sizes in excess of 10 m^2, with one fire in the three years included in the study reaching 50 m^2. While these results do not relate directly to the number of sprinklers operating, it appears unlikely that such large fires are compatible with the more common experience that in most cases sprinklers will open when fires reach between 0.5 and 2 m^2. See also Morgan [8] and the discussion in Chapter 3 of Morgan et al [4]. It follows that the assumption that the size of fire which triggers the first sprinkler is a reasonable size for design, is at best an unsupported assertion and will not be employed further in the present paper.

It may be noted that time-dependent calculation methods (i.e. "growing fire" methods) would be both reasonable and appropriate where there is good supporting evidence (e.g. where experimental growth curves exist for specific fire loads burned under controlled conditions). Such results for general retail fuel loads are largely absent from the published literature. The present paper will be developed entirely in terms of "steady-state" design fires, and will adopt the value of 2.5 MW, 2.2 m x 2.2 m currently widely used in the UK for retail areas where Quick Response sprinklers are used.

The mixing of air into the plume above the fire must make allowance for any tendency of the incoming air to cause the plume to "lean" with a consequent increase of mixing. It is not certain that this effect has been considered in existing designs of SHEVS Cabins. We then have [4]:

$$M = C_e PY^{1.5} \qquad (1)$$

where M is the mass flow rate of hot gases entering the reservoir (kgs^{-1}), C_e = 0.21 for a non-leaning plume where the ceiling is low, and 0.34 where the plume is leaning; P is horizontal perimeter of the fire (m), and Y is height of the base of the reservoir layer above the floor (m).

Where more than one side of the cabin is open, or where the single opening is very wide, we can use the value C_e = 0.21, and where the ceiling is also high C_e = 0.19. The low ceilings found in most cabins leads to the adoption of the former value. A relatively narrow single-sided opening requires C_e = 0.34. Note that in the case of the example Cabin, with a 2.2 m x 2.2 m fire and a single open side, the design is very close to the criterion (cabin width five times the fire width) [4] for selecting between values of C_e, and it is not certain which value should apply. It is therefore best to calculate for both and use the most pessimistic result.

The layer temperature close to the plume is:

$$\theta = \frac{Q_f}{C_p M} \qquad (2)$$

where θ is the temperature of the gases above ambient (K), Q_f is the convective heat flow resulting from the fire (kW), and C_p=1.01 $kJkg^{-1}K^{-1}$ is the Specific Heat of Air at constant pressure.

We can allow for some sprinkler cooling by taking the average gas temperature being exhausted by the fan/s (θ_{ave}) as midway between θ and the sprinkler operating temperature above ambient [4] - and approximating this last to 50 Degrees Celsius, we get:

$$\theta_{ave} = \frac{(\theta + 50)}{2} \qquad (3)$$

The minimum possible depth of smoke layer in the Cabin reservoir for smoke to flow towards the exhaust openings (D_{min}) must be estimated [4], where the flow out of the opening is treated as being a parallel, essentially two-dimensional, flow:

$$D_{min} = \frac{0.36}{C_d}\left[\frac{MT}{\theta^{0.5} W T_o^{0.5}}\right]^{2/3} \qquad (4)$$

where D_{min} is in metres, T_o is the absolute ambient temperature, taken to be 298 for the present example (K), T = T_o+ θ (K), W is the width of the cabin (m), C_d is a effective discharge coefficient at the open side/s of the cabin, C_d is 1 if no downstand is present at right angles to the flow, and 0.6 if a deep downstand is present at right angles to the flow (as in the example cited in the present paper).

The total fan capacity needed to prevent the smoke layer deepening is:

$$V = \frac{M(298 + \theta_{ave})}{352} \qquad (5)$$

where V is the total fan capacity from the cabin smoke reservoir (m^3s^{-1}).

The results of these calculations are presented in Table 3, where the design has been rejected if the minimum layer is deeper than the available depth. The design has been listed as "maybe" if the layer temperature is high enough for heat radiation to be a problem to people escaping beneath (i.e. assumed for the present paper to be > 200 ^oC). The cabins are sufficiently small that everyone in the affected cabin can be expected to have evacuated safely before the fire becomes life-threatening; and so the high temperatures may not be a serious problem.

It can be seen from Table 3 that only the last option is unambiguously valid, and that in view of the marginal status of the decision as to the correct value of C_e even this does not carry a high level of confidence. If one is willing to accept high temperatures in the layer then there is a greater range of validity, and the best design option is then to have a fan capacity of 11.3 m^3s^{-1} together with a downstand curtain material able to withstand very high temperatures - note that this last would be advisable anyway, as the fire might be located very close to part of a downstand curtain.

It follows from these equations that there will be fewer problems if the cabin is larger – and especially if it is higher, with a deeper smoke reservoir, and with larger exhaust capacity. It may not be practicable to increase the size, however, for other reasons unconnected with fire.

Table 3: Design parameters for a SHEVS Cabin

C_e	Y	Available Layer Depth (m)	θ	θ_{ave}	D_{min}	V	Is design valid?
0.21	2.5	0.5	339	195	0.93	10.2	No
0.21	2.25	0.75	397	223	0.67	9.2	Maybe
0.21	2.0	1.0	474	262	0.59	8.3	Maybe
0.34	2.5	0.5	209	130	1.07	14.3	No
0.34	2.25	0.75	245	148	0.95	12.8	No
0.34	2.0	1.0	292	171	0.83	11.3	Yes

2.4 Secondary Design Problems with the SHEVS Cabin

2.4.1 Sprinkler downdrag

It is known that sprinkler sprays can sometimes drag smoke downward out of a buoyant smoke layer. See for example the PhD Thesis by Williams [16]. It is less well known that the effect is stronger when the sprinkler spray is close to a wall. This effect was studied experimentally by Webb et al of the Fire Research Station [17], and it can be noted that smoke begins to be pulled down close to walls for water flow rates two-thirds of the value away from the wall. The retail cabin is relatively small, and most of the sprinklers will be reasonably close to walls or to the downstand above the front opening. The importance of the effect in practice cannot be calculated, but observers of experiments in the Fire Research Station's "sprinklered calorimeter" test rig (7 metres x 6 metres) [12] have often noted that once sprinklers activate the curtains containing the smoke reservoir need to be made deeper to prevent smoke escaping beneath the curtains.

This effect raises the possibility that the downstand depths assumed in the design calculations of 2.3 above may not be sufficient once sprinklers start to operate. This effect has never previously been considered in any SHEVS Cabin designs known to the present author.

Experiments at the Fire Research Station with the "sprinklered calorimeter" test rig have led to observations that sprinkler operation leads to the deepening of smoke and sometimes to the spillage of still-buoyant smoke beneath the downstand at the open front of the rig. This smoke has enough buoyancy to rise higher. No smoke has been observed being driven out of the rig at floor level. Unfortunately these observations were not made as part of a systematic study, but were incidental observations during experiments studying other aspects of fire. This suggests that it is desirable for a research study to be carried out specifically to study the sprinkler-induced spillage phenomenon. It also suggests the possibility that the use of a HVAC/ACMV system, or of a dedicated smoke clearance system to remove any smoke which drifts upwards from the open frontage, may be sufficient to prevent the creation of a hazard arising from the spillage. Where the ceiling outside the cabin is very high, even this may not be needed.

2.4.2 Leakage of smoke through gaps at the edges of automatic smoke curtains

Automatic smoke curtains consist of a roller box fixed to a firm soffit, which contains the fabric when the curtain is not deployed; the flexible fabric of the curtain itself; and a bottom bar fastened to the fabric which keeps the fabric taut when in the deployed position. The bottom bar may run freely in vertical tracks fastened to the structure (which would be the sidewalls in a cabin, close to the front edge), or much more commonly in practice will hang freely.

It is possible to minimise the gaps between adjacent curtains by overlapping the fabric, in which case greater rigidity can be obtained by conjoining the adjacent bottom bars.

There will always be an imperfect seal where the fabric of the curtain meets the side wall - especially so where there are no vertical tracks for the bottom bar (Figs. 2 and 3). The width of the edge gaps between the fabric and the structure will depend on many uncontrollable factors - not least the accuracy of construction of the cabin, and of the fitting of the curtain. There has never been a study of these gaps, but visual inspection of many curtains suggests that, for reasonably skilled fitting, a width of 30 mm is a realistically pessimistically large value. Note that where two drop curtains adjoin each other at an angle, much larger gaps are common. This last arrangement is not good practice (but can often be found in practice).

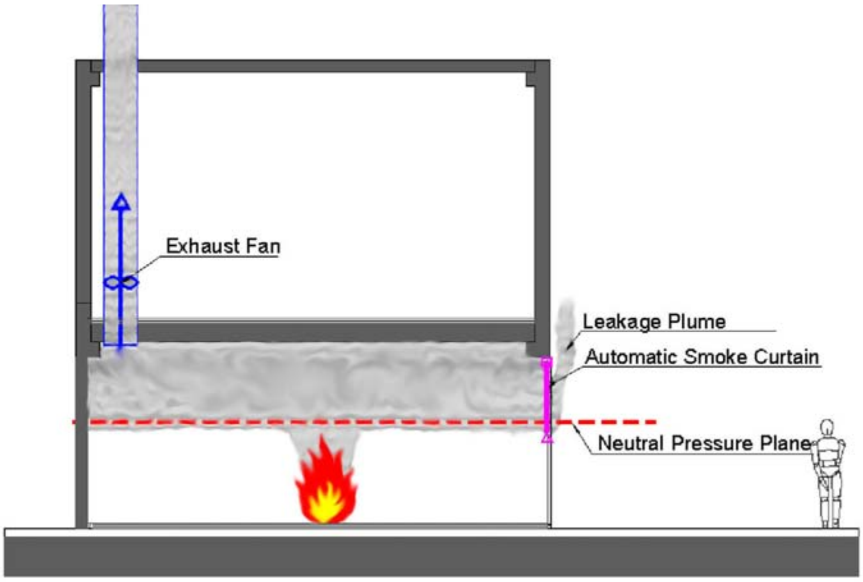

Fig. 2: The SHEVS Cabin-Curtain edge leakage – section through cabin

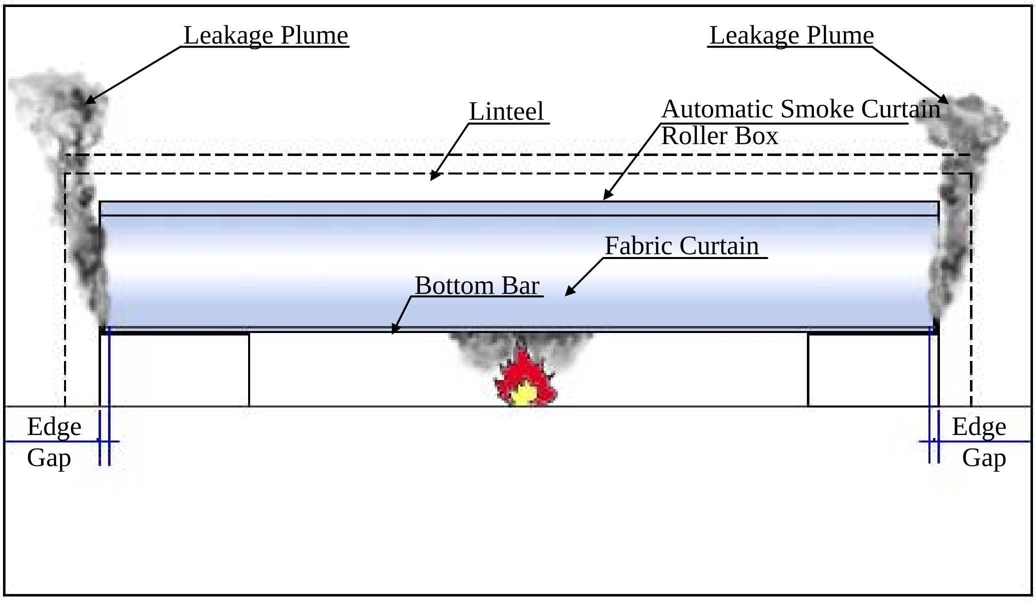

Fig. 3: The SHEVS Cabin-Curtain edge leakage – front view of cabin

In the fire condition, we expect to have a hot, buoyant, smoke layer in the cabin, in contact with the smoke curtain at the front opening, and almost as deep as the curtain at the front of the unit. As for any thermally buoyant layer, the further above the base of the layer the greater will be the buoyant pressures. Where the opening into the cabin is large (which it will be in the case of a SHEVS cabin) there will be very little pressure drop across that opening. The height at which the pressure on one side of a barrier is equal to the pressure on the other side is known as the Neutral Pressure Plane. With a trivially small pressure drop across the large inlet, this Neutral Pressure Plane can be taken to be at the bottom of the drop curtain.

It follows therefore that the increasing buoyant pressures with increasing height will always serve to push smoky gases out through the edge gaps into the main space which we are trying to keep clear of smoke. Note that this effect has never been described for any of the existing SHEVS cabin designs.

The leakage of smoke through edge gaps has been studied experimentally by Garrad et al. [18], who arrived at an empirical formula:

$$M_{leak} = A_{gap}\left(\frac{352.2}{T_{max}}\right)\left(\frac{2gd_{gap}\theta}{T_{amb}}\right)^{0.5} \tag{6}$$

Where M_{leak} is the mass flow rate of smoke through a single edge gap (kgs^{-1}), A_{gap} is the vertical area of the edge gap (m^2), d_{gap} is the depth of hot smoke below the top of the edge gap (m), T_{amb} is the ambient air temperature in Kelvin (K), T_{max} is T_{amb} + θ (K), and g is the acceleration due to gravity (ms^{-2}).

If we use parameter values appropriate to the same example as before, for the optimum SHEVS design identified in Section 2.3 above, we find for two edge gaps each of 30 mm width, for a layer temperature θ of 356 K (chosen to give a worst case amount of leakage), and for a curtain 0.6 m deep (taking advantage of a fixed downstand of 0.4 m assumed to be present so that the curtain is located below this downstand); we get from equation (6) that:

M_{leak} = 0.074 kgs^{-1}

The visibility in this smoke could be very low at the leakage gap - experience of various tests suggests that the smoke may need to be diluted between 100 and 400 times with clean air before it becomes acceptable on an escape route. This should not be a problem if the main space is sufficiently large, and if the HVAC or a dedicated smoke clearance system in that space has enough capacity to achieve adequate dilution, or to exhaust the relatively small amount of smoke from above the opening and any exposed escape routes. It can be a problem however in spaces where the air is effectively stagnant, allowing smoke to accumulate.

2.4.3 Deflection of free-hanging smoke curtains

There will be a tendency for the air being drawn into the cabin beneath the curtain to drag that curtain sideways. This has been studied by Ghosh [19] who has shown that:

$$d_d = \frac{1.3\rho_{amb}v^2 d_l^2}{2g(2M_b + M_c L)} \tag{7}$$

where d_d is the horizontal deflection away from the vertical of the bottom bar (m), ρ_{amb} is ambient air density (kgm^{-3}), v is the air velocity beneath the curtain (ms^{-1}), d_l is the vertical height of the curtain above the smoke layer base (m), M_b is the mass per metre of the curtain's bottom bar (kgm^{-1}), M_c is the mass per unit area of the curtain fabric (kgm^{-2}), L is the length of curtain from top to bottom measured along the curve of the fabric (m).

For the present example, based on the optimum design identified in 2.3 above, we can assume that L is approximately equal to d_l. If we assume M_b is 2 kgm^{-1}, and M_c is 0.5 kgm^{-2}, (both values are typical of many curtains available commercially) we obtain:

d_d = 0.0018 m

This is negligible.

The buoyancy of the hot smoke layer will push the curtain in the opposite direction - i.e. outwards from the cabin front. This effect has also been described by Ghosh [19], such that:

$$d_d = \frac{1.2\rho_{amb}\theta d_l^3}{3T_{max}(2M_b + M_c L)} \tag{8}$$

In the interests of pessimism, we can take θ = 356 K, and other values as before, giving:

d_d = 0.013 m

This is also trivial in the context of the cabin, especially so because the curtain hangs between parallel side walls. Note however that these effects can become significant where there are no side walls, or where the gap sizes may increase as the curtain deflects because of the shape (or absence) of the side walls in the deflected position.

2.4.4 Implications for fire safety management

The sensitivity to equipment failure makes the SHEVS cabin very dependent on there being an effective regime of maintenance and frequent testing of the functionality of all the equipment. It is also important that no significant amount of flammable material should be allowed to be located outside the line of the cabin opening (i.e. beyond the line of the smoke curtain or fixed downstand intended to contain the smoke layer). This in turn implies that the building's management must exercise a policing function directed towards the operators of the cabins in the building, to identify and correct any tendency for potential fuels (e.g. retail goods) to be placed on the wrong side of the line. It follows that fire safety management provisions are an essential part of the overall concept.

2.5 Summary of Conclusions about the SHEVS Cabin

- For the example cited, the optimum fan capacity is about 11.3 m^3s^{-1}.
- The successful operation of sprinklers in the cabin is essential.
- The design is not tolerant of failure in any of the equipment.
- Even in a successful design some smoke will leak past the edges of automatic drop curtains into the space outside the cabin. Whether this creates a hazardous condition or not depends on the volume of that space and the role and performance in emergency of any HVAC system in that space.
- Curtain deflection is trivial and can be ignored for the case of the cabin dimensions used in the example. Note that this conclusion cannot automatically be generalised to apply to other examples.
- The operation of sprinklers may cause some smoke to spill beneath the curtains unless the curtains can be made deeper - although this cannot be calculated. This could in some circumstances make the curtains close to or below head height for some people who might have to escape below it.
- The curtain material should be able to withstand flame temperatures. This is a more rigorous specification than is usual for most applications of smoke curtains.
- Fire safety management provisions to ensure continuing function of all equipment is essential.
- Fire safety management must include a "policing" role to prevent potential fuels being placed outside the cabin.

3. THE DEPRESSURISED CABIN

3.1 Principle

The principle is superficially similar to the SHEVS cabin, although actually very different. An automatic drop curtain is used to close off the full height of the opening to the cabin. Escape for people inside the cabin at the time of operation of the curtain must be provided for by some other means - e.g. by a door (or doors – in general Means of Escape from within the cabin must comply with local Codes and Regulations) which should itself be fire-resisting and fitted with smoke seals and intumescent strips. The interior of the cabin will be allowed to fill completely with smoky gases to the floor.

In the absence of any depressurising fan (Fig. 4) the major openings will now be the edge gaps between curtain and sidewalls. The buoyancy of the hot gases in the cabin will draw air in through the lower regions of the gaps, and push smoke out through the upper regions. To a good approximation we can regard the neutral pressure plane as being half way up the edge gaps. The amount of smoke leaking out into the Pier's main space will be described by equation 6, with d_{gap} now having the new definition of the depth of the Neutral Pressure Plane beneath the top of the edge gap. If we take the same dimensions as before for a worked example, the height of the opening is 2.6 metres, so d_{gap} becomes approximately 1.3 m, or twice the value adopted in section 2.4.2. It can clearly be seen from equation 6 that this will increase the amount of leakage by the square root of 2. In practice the temperature in the cabin is likely to be hotter than for the SHEVS cabin, which would further increase the leakage flow.

If there is an exhaust fan designed to reduce the pressure in the cabin by an amount equal to the buoyant head measured between the height of the "no-exhaust" Neutral Pressure Plane and the top of the edge gap, the effect will be to move the Neutral Pressure Plane to the top of the edge gap. In this case (Fig. 5) all leakage through the edge gap will be into the cabin, and no smoke at all will leak into the space outside. It can be expected that this reduced pressure in the cabin will tend to draw the curtain into the cabin. The magnitude of this effect is discussed below for a free-hanging curtain. If the bottom bar runs freely in vertical tracks fastened to the side walls of the cabin, there can be no horizontal deflection of the bottom bar. The pressure difference across the curtain can cause the fabric to bulge into the cabin, which in turn will cause the bottom bar to lift thus opening up a larger gap and causing the neutral pressure plane to fall in height. A calculation procedure for relating the weight of bottom bar and the length of fabric so as to allow the bar to stay on the floor is developed below.

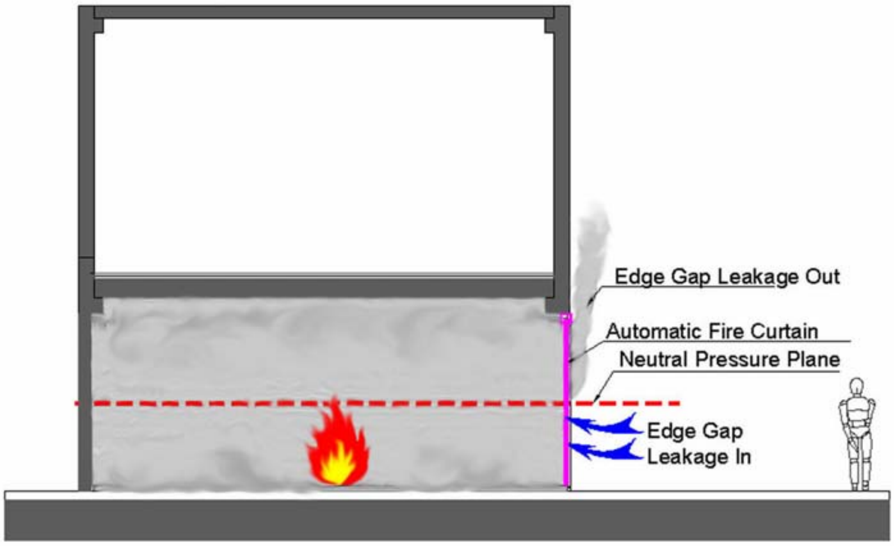

Fig. 4: The Depressurised Cabin-Principle – without depressurisation – section through cabin

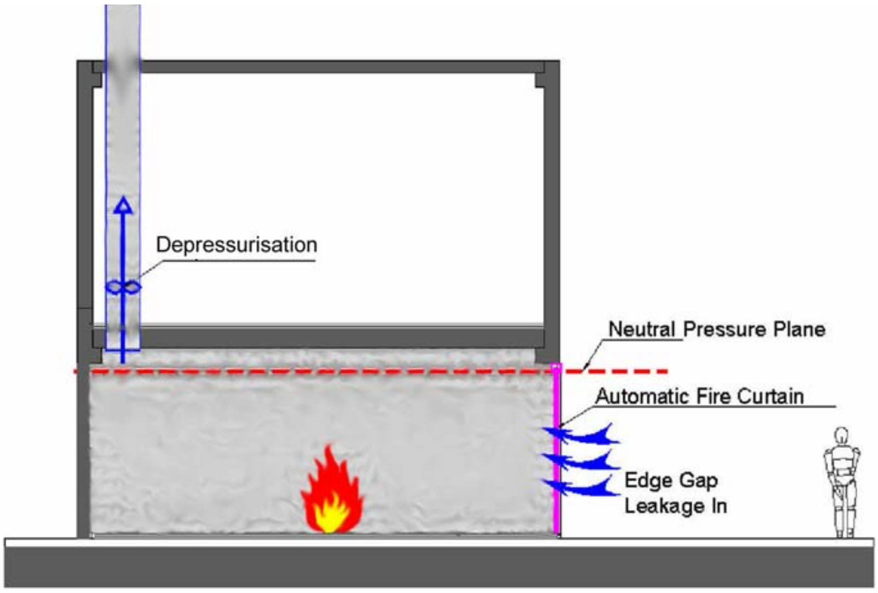

Fig. 5: The Depressurised Cabin-Principle – with depressurisation – section through cabin

Provided that the curtain fabric is able to withstand flame temperatures, and that the fans will keep running, this system will tolerate the failure of sprinklers in the cabin. If the fans fail, the leakage through the edge gaps will still be smaller than for the open fronted SHEVS cabin under similar failure conditions. In many applications this edge-gap leakage may be small enough to be dealt with by a HVAC system switching into 100% replacement-air mode. Simultaneous failure of both sprinkler system and fans will still only result in a relatively small amount of edge leakage, which in many applications will not cause a serious hazard to evacuation although it would remain undesirable. Note that simultaneous failure of sprinklers and fans in the SHEVS cabin would result in a catastrophic failure of the concept of "containment" of the smoke and fire gases. This implies that the fans can be rated for gas temperatures expected with sprinkler operation, and need not allow for sprinkler failure. It follows that with this concept there is a high degree of tolerance for equipment failure - with the exception of the smoke curtain, which MUST deploy successfully.

It follows that there are major implications for the Building's management, who need to re-test the functioning of the smoke curtain sufficiently frequently that any faults will be found and repaired quickly.

It remains to develop calculative design procedures for the depressurised cabin.

3.2 Pressure Differentials and Exhaust Fan Capacity

The buoyant pressure developed by a column of hot gases equal in height to the height of the top of the edge gap above the neutral pressure plane (no exhaust condition) is:

$$\Delta p_1 = \frac{\rho_{amb}\theta g h}{2T_{max}} \tag{9}$$

where Δp_1 is the pressure of the column of gases of height h/2 (Pa), h is the height of the opening to the cabin (2.6 m in the current example) (m), and the Neutral Pressure Plane has been taken to be half-way up the opening where there is no exhaust.

For the current example:

In the worst case where the sprinklers have failed, we can take θ to be approximately 1000 K, from which we obtain:

Δp_1 = 12 Pa

It follows that the exhaust fan must be able to generate a pressure difference of at least 12 Pa with ambient air leaking in through the full height of the edge gaps.

If we take this pressure difference (which actually applies at the no-fan Neutral Pressure Plane height half way down the opening) as being the average for the full height of the edge-gap, the air velocity in the edge gaps can be taken to be:

$$v_{gap} = \left(\frac{2\Delta p_1}{\rho_{amb}}\right)^{0.5} \tag{10}$$

where v_{gap} is the velocity in the edge gap (ms^{-1}) and the effective discharge coefficient of the edge gap has taken a value of 1.0 following the empirical result of Garrad et al. [18].

The mass flow rate of air entering the cabin through the gaps (M_{gap}) is:

$$M_{gap} = 2C_v A_{gap} v_{gap} \rho_{amb} \tag{11}$$

where M_{gap} is the mass rate of entry of air through the curtain edge gaps (kg) and C_v again takes the value of 1.0.

This incoming air will be heated before being exhausted by the fan, although the action of the sprinklers within the cabin will limit the temperature rise. The resulting temperature rise can be assessed by the following approximate procedure.

We can note that approximately 20% of the incoming air consists of oxygen. If we make the deliberately conservative assumption that the sprinklers do not reduce the efficiency of combustion, we can expect about a quarter of that oxygen to be used up before combustion becomes inefficient. Therefore the heat release rate in the cabin for these poorly-ventilated conditions will not exceed:

$$q = 0.05 M_{gap} c_{oxygen} \tag{12}$$

where q is the ventilation-controlled heat release rate (kW), c_{oxygen} is heat release per kilogramme of oxygen consumed ($kJkg^{-1}$).

We can adopt the value c_{oxygen} = 13,100 $kJkg^{-1}$ by analogy with the common practice adopted in Cone and Large-Scale calorimetry.

If we make another deliberately conservative assumption that we can ignore all heat losses, the gas temperature in the cabin (also denoted θ_{max} for present purposes, by analogy with the SHEVS Cabin) would become:

$$\theta_{max} = \frac{q}{C_p M_{gap}} \tag{13}$$

where θ_{max} is the unsprinklered maximum theoretical temperature rise of the gases (K).

Because q in these conditions of restricted ventilation will be relatively small compared to a well-ventilated SHEVS cabin, and because the fan capacity (still to be calculated) can also be expected to be small compared to the SHEVS cabin, we can expect gases in the cabin to remain subject to the cooling action of sprinkler sprays for a longer time before being exhausted. Hence we can expect the effectiveness of spray cooling to be greater than for the SHEVS cabin in terms of reducing temperature. In these circumstances it would not be reasonable to adopt Equation (3) above for the Depressurised Cabin. The assumption is made here (arbitrarily) that for the Depressurised Cabin Equation (3) can be rewritten as:

$$\theta_{ave} = \frac{\theta_{max} + 50}{3} \quad (14)$$

Combining Equations (12) to (14),

θ_{ave} = 233 K

The fan capacity required, at a temperature of θ_{ave} , is given as before by Equation (5), which using Equations (11) to (15) and for T_{amb} = 290 K can be simplified to:

$$V_{fan} = 7.13 A_{gap} \left(\frac{\Delta p_1}{\rho_{amb}} \right)^{0.5} \quad (15)$$

The vertical area of a single edge gap is simply the width of gap times the height of the curtain.

$$A_{gap} = w_{gap} h \quad (16)$$

where w_{gap} is the width of the edge gap (m), and h is the height of the opening of the front of the cabin (m).

With Δp_1 = 12, w_{gap} = 0.03, h = 2.6, we get from equations (10) to (16):

V_{fan} = 1.75 m^3s^{-1}

Note that this is much smaller than would be possible for the equivalent SHEVS Cabin. This implies not only a cost saving on the fans themselves, but also on any ducts used to carry the gases to the exterior of the building.

If the edge gaps are smaller than assumed, as would be the case with a better standard of fitting of curtains, these same equations tell us that the value of Δp_1 will increase.

The force needed to open the door by people escaping (note that the door must open in the direction of escape, and so the pressure difference will tend to hold it closed) must not be excessive. It is proposed that we can follow the precedent set by the British Standard 5588 Part 4 (1998) [20] in allowing a maximum force on the door handle of 100 Newtons. For a single-leaf door of approximately 2 m^2, and with the door handle close to the edge of the door and the centre of pressure being in the centre of the door, the pressure difference to be overcome is numerically approximately equal to the force required at the door handle. It follows that the pressure difference must never be allowed to exceed 100 Pa. Lower door-opening forces will benefit the infirm or the very young (see for example Read and Shipp, 1979 [21]). It is here suggested that an upper limit of 60 Pa should be adopted as an additional safety margin wherever the public is likely to be present in a cabin.

The pressure differences can be limited by fitting into the walls or door of the cabin a barometric damper. This device has been developed for use with pressure differential smoke control systems. They operate by opening either against a spring or against a pre-set counterweight when the pressure difference exceeds a pre-selected value. Such devices are available commercially, having been developed for use with pressurisation systems (see for example Reference 20). The aerodynamic free area of such a damper must not be less than:

$$C_v A_{damp} = \left(\frac{\rho_{amb} V_{fan}^2}{2 \Delta p_2} \right)^{0.5} \quad (17)$$

where C_vA_{damp} is the aerodynamic free area of the barometric damper in the open position (m^2), Δp_2 is the maximum acceptable pressure difference between inside the cabin and outside (Pa).

For V_{fan} = 1.75 m^3s^{-1} and Δp_2 = 100 Pa, we get:

C_vA_{damp} = 0.14 m^2

One can note here that larger area barometric dampers can be set to operate at lower pressure differences. For example, if we take Δp_2 to be 60 Pa, the aerodynamic free area needed for the barometric damper only increases to 0.18 m^2. These areas are sufficiently small that there ought to be no difficulty in finding a location to fit such a damper. The best place to fit it would be close to the floor, perhaps in the door itself, in order to minimise the temperatures to which the damper is exposed.

3.3 Deflection of Free-Hanging Curtains

The effect of depressurising the cabin will be to pull the curtain at the front of the cabin towards the interior of the cabin. Only the weight of the bottom bar and of the fabric will oppose this. The horizontal deflection is given by equation (7), and the air velocity through any gaps is given by equation (8). It still remains to calculate the vertical length of the fabric, measured along the curve (L in equation (7)). An iterative procedure is given by Ghosh [19], such that:

$$L = d_1 + d_d \tan\left(\frac{\tan^{-1}\left(\frac{d_d}{d_1} \right)}{2} \right) \quad (18)$$

The method adopted is to use equation (10) to solve for v_{gap}, set $L = d_l$; solve equation (7) for d_d; use this value in equation (18) to solve for L, use this value of L in equation (7), and continue until values of L and d_d become stable.

Using the values appropriate to the current example, with Δp_1 = 12 Pa, w_{edge} = 0.03 m and d_l = 2.6 m, equation (10) gives:

$v_{gap} = 4.5\ ms^{-1}$

We can assume that when the curtain's bottom bar is on the point of losing contact with the floor and of starting to lift, the initial air velocity beneath the curtain will take this same value.

Using this value in equation (7) to give an indication of the magnitude of horizontal deflection for a free-hanging smoke curtain at this point where the bottom bar starts to lift, and following the iterative process stated above, and assuming very heavy values of M_b = 10 kgm^{-1} and M_c = 0.5 kgm^{-2}, we get:

$d_d = 0.51$ m
L = 2.65 m

This means that with the heaviest commercially-available bottom bar, the curtain will need a fabric length of 2.65 m in order for the bar to remain in contact with the floor, and that the bar will be 0.51 metres away from the vertical plane below its suspension line. The further implication is that there must be nothing placed in the way of this deflection, otherwise the bar will twist and open up much larger gaps to the sides, which will in turn allow smoke to escape into the space outside the cabin. It will be very difficult to enforce and maintain this "cordon sanitaire" with the retail unit in everyday use. Consequently it would be much better if the curtain were to have its bottom bar running freely in vertical tracks in order to prevent any horizontal movement of the bar.

Another disadvantage of this approach is that, as can be seen from equations (7) and (10), the horizontal deflection is approximately directly proportional to the pressure difference Δp. This is in turn approximately proportional to the width of the edge gap squared for a given fan capacity (see equations (10) and (15)). It follows that the horizontal deflection is very sensitive to the width of the edge gap and hence to the accuracy of fit of the curtains. This sensitivity is another reason why it would be better to have the bottom bar moving in vertical tracks and so to have its horizontal movement restrained.

3.4 The Relationship between Curtain Length and the Tendency of the Bottom Bar to Lift when Constrained by Side Tracks

A curtain which is constrained to have its bottom bar freely moving in vertical tracks mounted on the side walls is affected by the pressure difference across it. It will "billow" in the shape of the sail on a square-rigged sailing ship. If there is too little fabric in the curtain, the bottom bar will rise, thus failing to achieve the floor to ceiling closure which is desired.

In developing a design relationship for this type of smoke curtain, we can ignore the outward buoyant pressure, and also the effect of the weight of the curtain fabric, since both of these effects will tend to oppose the tendency of the bottom bar to lift. Ignoring these effects will err on the side of safety.

Consider the forces represented in Fig. 6.

The total force on the curtain (per unit width of opening) acting inwards is:

$\Delta p d_1 \quad (Nm^{-1})$

The forces opposing this and preventing movement occur at the top of the curtain at the roller box, and at the bottom bar where it is constrained by its tracks. Hence the horizontal reaction at each of these locations is (per unit width):

$$\Delta p \frac{d_1}{2}$$

At the bottom bar, this is equal to the horizontal component of the resultant tension force in the curtain fabric.

At the bottom, when the forces are such that the bar is on the point of lifting, the vertical component of the tension in the fabric just supports the weight of the bar. I.e. the vertical component of the resultant force is (per horizontal metre of curtain).

$M_b g$

If follows from Fig. 6 and these results that:

$$\mathrm{Tan}\alpha = \frac{2M_b g}{\Delta p d_1} \tag{19}$$

$$\mathrm{Tan}\beta = \frac{\Delta p d_1}{2M_b g} \tag{20}$$

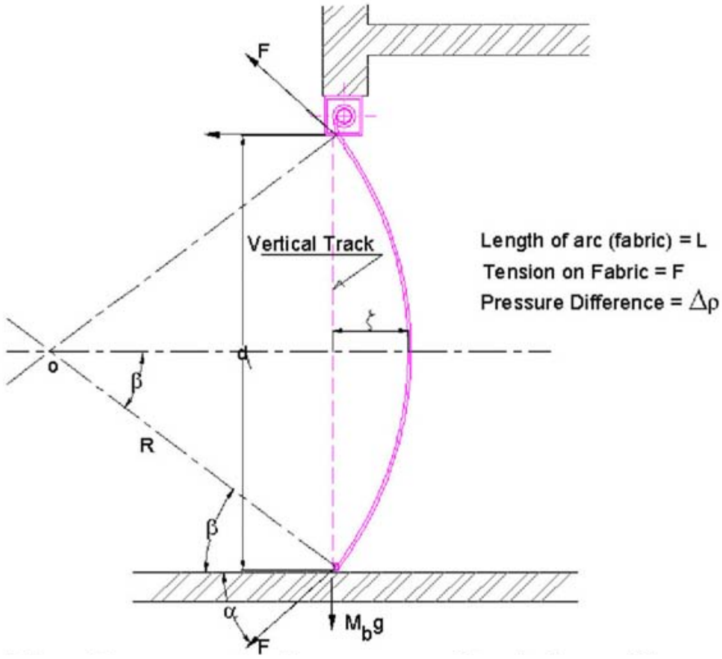

Fig. 6: The forces acting on a curtain with constrained bottom bar - section

where α is the angle between the horizontal component of the tension in the curtain fabric, and the resultant force; and β is the angle between the vertical component of the tension in the fabric and the resultant force: both angles being determined at the bottom bar.

We can assume that the curve of the curtain is the arc of a circle, of radius:

$$R = \frac{d_l}{2\mathrm{Sin}\beta} \tag{21}$$

We also have that:

$$\frac{L}{2\pi R} = \frac{2\beta}{360} \tag{22}$$

where β is in degrees, and L is the length of the curtain fabric measured along the arc, in metres.

By combining equations (21) and (22), we get:

$$L = \frac{2\pi d_l \beta}{360\mathrm{Sin}\beta} \tag{23}$$

In summary, any length of curtain fabric greater than L calculated in this way will allow the bottom bar to rest on the floor without lifting.

If we insert values appropriate to the current example, we can take the upper limit value of 60 Pa for Δp in order to allow ease of opening the escape door; and if we assume a heavy bottom bar of 10 kgm^{-1}, d_l is 2.6 metres, we find from equations (5) to (23) that:

$\beta = 38.5^{o}$ and L = 2.81 m

This means that for the bottom bar to remain on the floor up to the preferred pressure for the barometric damper to open, the curtain needs to have at least an additional 0.21 metres of "slack".

If we repeat the calculation for a bottom bar of 2 kgm^{-1}, we get:

$\beta = 76^{o}$, L = 3.55 m

Or in other words there needs to be an additional 0.95 m of fabric in the curtain. It follows that there is a trade-off between the length of fabric and the weight of the bottom bar.

The horizontal offset of the centre of the "bulge" of the curtain is given by:

$$\varsigma = R - R\mathrm{Cos}\beta \tag{24}$$

which can be combined with equation (21) to give:

$$\varsigma = \frac{d_l}{2}\left[\frac{1}{\mathrm{Sin}\beta} - \frac{1}{\mathrm{Tan}\beta}\right] \tag{25}$$

For the case of $M_b = 10$,

$\zeta = 0.45$ m

For the case of $M_b = 2.0\ kgm^{-1}$,

$\zeta = 1.01$ m

It follows that a heavy bottom bar will cause fewer problems of physical clearance of displays of goods inside the unit, and so is likely to cause fewer problems during the regular functional tests which are desirable for such an essential component of the system.

It should also be noted here that ζ has been calculated for its "worst-case" where there is no leakage past the curtain's edge gaps (i.e. the curtain is a perfect fit) and all the air enters through the barometric damper.

3.5 Summary of Conclusions about the Depressurised Cabin

- The cabin should have fire-resisting walls and ceiling.
- The drop curtain at the front opening should have a bottom bar which moves freely in vertical tracks fastened to the side walls of the cabin.
- This curtain should be able to withstand flame temperature gases of at least 1 000 ^oC.
- The curtain must be full height, with its bottom bar resting on the floor.
- The curtain should be longer than the vertical height to the floor, with a fabric length calculated to be sufficient to prevent the bottom bar lifting.
- The bottom bar should be heavy, with the weight specified as part of a design trade-off with the overall fabric length, in order to optimise intrusion of the curtain into the retail space. For the example cited a bottom-bar weight of 10 kgm^{-1} appears suitable.
- A relatively small exhaust fan, of 1.75 m^3s^{-1} for the example's dimensions of cabin, should be used to achieve the reduction of pressure in the cabin.
- The cabin should have a barometric damper set to open at 60 Pa. For the example cited the damper should have a minimum aerodynamic free area of 0.18m^2.
- There must be an escape door from the cabin for people to escape after the curtain has operated. This door should be identified by appropriate signage.
- The system is tolerant of failure of all components except the smoke curtain, which must work properly. This implies that the management of the Terminal Building must include regular, frequent, functional tests of the curtain during normal use.
- As in the case of the SHEVS cabin, the fire safety management should include a "policing" role to prevent potential fuels being placed outside the line of the smoke curtain, and also to ensure that the fall of the curtain is not blocked.

4. OVERALL CONCLUSIONS

The depressurised cabin principle allows a greater tolerance to equipment failure than the SHEVS cabin principle used in other modern airports. It is also less susceptible to uncalculatable disadvantageous secondary problems of sprinkler downdrag, and to problems of smoke leakage through the gaps at the edges of the smoke curtains. The fan capacities are smaller, and it is expected that equipment costs will be less.

It is better to use a smoke curtain with its bottom bar running in vertical tracks fastened to the side walls than to use a free-hanging smoke curtain.

Design methods have been described, and where necessary developed, and the design parameters have been evaluated for a representative retail unit of a type which might be found, for example, in an airport terminal building.

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APPENDIX 1: FIRE SIZE AT ONSET OF FLASHOVER IN A COMPARTMENT: A BRIEF OUTLINE OF CALCULATION PROCEDURES

The purpose is to calculate the fire size (in terms of heat release rate) which is just sufficient to cause flashover in a compartment. Flashover is defined for the present purpose as the onset of radiation-induced ignition of fuel materials remote from the original fire due to the downward heat radiation from a buoyant ceiling layer of fire gases. A layer temperature of 550 ^{o}C above ambient is used as the flashover criterion. This represents a reasonable compromise between the various temperature criteria found in experiments.

There are several procedures available, each with its own strengths and weaknesses.

The first test is whether the compartment of interest is similar in size (volume) to the experimental compartments used as a basis for the correlation developed by McCaffrey et al [22]. The largest of these was only c. 30 m^3. The upper limit for using McCaffrey's correlation has rather arbitrarily been set for the present purpose at 40 m^3. Even for these small compartments the correlation should only be used by itself if the opening from the compartment is taller than it is wide: as in the original experiments. Where the opening is wider than it is tall no current theory strictly applies. These properties make this correlation inappropriate for the present example.

For larger compartments one can use a method based on 'The onset of Flashover in Compartments' - published as a paper in the FRS/SFSE Symposium at FRS in 1989 [23]. The calculation takes account of the opening geometry: that is whether the opening is wider than its height or the opposite; and whether there is a deep downstand at the opening or not. This procedure is essentially the same as for equations (1) to (4) above, with θ taken to be 550 ^{o}C and solving for Q_f with a default assumption of a convective heat release density of 500 kW per m^2 of fire.

Where no details of the fire are specifiable, one can use an idea suggested by Prof. Thomas [24], namely that flashover is likely to occur for fast growing fires when flames touch the ceiling. A flame plume correlation by Cox and Chitty [25] is used to estimate flame height, with the axial plume temperature at the tip of the flame taken to be a time-averaged value of 550 ^{o}C. This gives:

$$q = (7.85h)^{2.5} \qquad \text{(A.1)}$$

where q is the heat release rate (kW), and h is the height to the ceiling (m).

Note that in large compartments this flame-height hypothesis is likely to be more accurate than Morgan's large-compartment/wide-opening model for fast-growing fires, but is likely to be less accurate for slower growing fires.