Access design

A recent modelling study has highlighted the risk of fire gases in a corridor igniting as firefighters access a residential apartment. **Paul Grimwood** looks at the implications for smoke ventilation design and fire service tactics

WHEN DESIGNING for automatic fan-assisted ventilation to common areas of multi-storey residential buildings, the fire engineer will commonly utilise a worst-credible single compartment design fire of 2MW to 4MW, producing well-ventilated post-flashover conditions.

This approach may be acceptable to enhance an evacuation strategy, providing functional requirements are met according to established guidance. However, when designing to assist firefighting access, the worst-credible fire scenario upon which to base a design may not be a well-ventilated scenario.

A computer zone modelling study undertaken by Kent Fire and Rescue Service has explored this further by analysing data from 14 design scenarios involving different natural and fan-assisted smoke ventilation systems.

Remote ignitions

According to data from the Government, post-flashover room fires (<4MW) are confined to the compartment of origin in around 10% of all building fires, whereas post-flashover multi-compartment fires (>5MW) are noted in a further 10% of such incidents. It has also been observed that, in a smaller number of fires (0.5%), there is some form of abnormal behaviour involving the fire gases that occur beyond or outside the compartment of origin – often referred to by firefighters as 'remote ignitions'. These ignitions of smoke are sometimes related to 'auto-ignition' of combustion products and in other instances may be termed 'backdraughts', 'flash fires' or 'smoke explosions'.


The study sheds new light on fire gas burn-offs in corridors and the tactics of firefighters when opening a compartment to gain access

As confined compartment fires only surpass the flashover stage in around 10% of fires, the generic approach to design may meet the demands of <85% of likely scenarios. However, such an approach fails to address the more extreme, although rare, circumstances when firefighters may be entering grossly under-ventilated fire conditions, where fire development may be very sudden and intense.

It has been estimated that such extreme fire development may only occur once in every 180 building fires, although experience has demonstrated that these events present a clear potential to cause serious injury to firefighters.

While it might be assumed that flashover is the most dangerous event associated with rapid fire development, the potential for compartment backdraught or remote ignitions of fire gases outside the fire compartment are of major concern because they are perhaps the most difficult for firefighters to deal with.

The duration of such fire gas burn-offs may exceed >300 seconds, culminating in full compartment (for example, corridor or stair-shaft) flashover. The existence of any ventilation openings or smoke shafts could have a major impact on the duration and severity of these gas ignitions, placing firefighters at risk.

This article presents data from a series of zone models produced by Kent Fire and Rescue Service, which offers some guidance on the conditions that might lead to rapid fire development while gaining access to the fire.

Some 14 stair and corridor ventilation configurations were simulated and analysed across >70 variations of corridor and vent geometry. Where fire gas ignitions occurred, they were each variable in duration and intensity. However, in some situations, firefighters may have occupied an untenable environment that could have resulted in serious injury or death.

Design fire

The study used data that the National Institute of Standards and Technology (NIST) produced for a computer model of an apartment fire in New York City.

In March 1994, the New York City Fire Department (FDNY) responded to a fire in a three-storey apartment building in Watts Street, Manhattan. On arrival, there were little signs of fire. Firefighters were deployed to the first floor and into the stairs above the fire apartment.

When the door to the first-floor apartment was forced open, a flow of warm air (100°C) issued from the apartment, which very quickly turned into a large door flame transporting into the hall and up the unprotected stairway, engulfing three firefighters at the second-floor landing. The flame persisted for some 6½ minutes, resulting in their deaths.

FDNY requested the assistance of NIST to model the incident in order to understand the factors which caused such an event. The NIST CFAST model was able to reproduce the observed conditions, and supported a theory of the accumulation of significant quantities of unburned fuel from a vitiated fire in an apartment which had been insulated and sealed for energy efficiency.

Data inputs

For the purposes of the Kent Fire and Rescue study of under-ventilated fire conditions, comparing various ventilation arrangements in access corridors, the core data inputs used by NIST in the Watts Street apartment fire were repeated for consistency in all models, except for the fire behaviour training unit, where inputs were more relevant to a much smaller fire compartment and a controlled fire load with an earlier door entry at 800 seconds. The fire area in the Watts Street apartment measured $85.4m^2$ with a 2.5m ceiling.

In the NIST model, the apartment fire grew to about 500kW over 5 minutes simulation time, then rapidly throttled back as the oxygen concentration dropped below 10%. Temperatures in the apartment peaked briefly at about 300°C and then rapidly dropped below 100°C as the burning rate fell. The concentration of carbon monoxide rose to about 3,000ppm and a large amount of unburned fuel accumulated within the apartment volume during this stage of vitiated combustion. On opening the apartment door at 2,250 seconds, the door flame grew within a few seconds to 5MW, with stair temperatures in excess of 1,200°C, while conditions in the apartment remained relatively cool (lower layer temperature <160°C).

The Kent study used original data inputs from the NIST Watts Street simulation representing a grossly under-ventilated fire compartment, but a 15m long corridor was also added between the fire apartment and the stairs to enable a range of venting solutions and smoke shaft arrangements to be modelled under the same fire conditions. In all cases, the automated ventilation was activated at 1,800 seconds into the simulations, with door entry to the fire compartment timed at 2,250 seconds.

Fire behaviour

An understanding of practical fire behaviour supports a view that the CFAST computer zone models produced in the Kent study represent viable corridor flashovers where ventilation arrangements may serve to influence fire development. In most situations, the remote corridor ignitions of unburned combustion products are made worse by forced or natural air-flow paths that cause depressurisation of the corridor, or a substantial movement of air through and beyond the space.

In each situation as modelled, the under-ventilated combustion products generally ignite in the corridor, although the duration and intensity of gas burn-offs vary. In some situations, the corridor is seen to depressurise, causing more combustion products to be drawn out of the apartment to mix with air in the corridor.

Such ignitions in the gas layer may demonstrate one or more of the following scenarios:

- low-intensity high-level flaming at the ceiling (may be hidden in the smoke)
- flaming at the smoke/air interface
- backdraught
- smoke explosion
- full corridor flashover

Table 1: CFAST computer zone models

Ventilation system		Simulation/design scenario
Natural	1	Steel container fire behaviour training unit (under-ventilated door entries)
	2	Baseline unventilated 15m x 1.8m x 2.4m high
	3	Unventilated corridor with stair 1.0m^2 automatic opening vent (AOV) and door to stairs fully open
	4	Corridor with stair 1.0m^2 AOV and door to stairs fully open – and 0.5m^2 window AOV in corridor open
	5	Single 1.5m^2 window AOV in corridor open
	6	Approved Document B 1.5m^2 natural shaft
	7	2 x 750m^2 natural shafts (non code compliant)
Fan extract	8	Mechanical extract 0.65m^2 shaft to 2m^3 per second – with natural make-up shaft
	9	Mechanical extract 0.5m^2 shaft to 4m^3 per second – make-up air from stairs
Fan flushing (dilution)	10	2 x 0.75m^2 shafts (one serves as a 3m^3 per second mechanical flushing shaft and the other as natural extract)
	11	1 x 0.75m^2 3m^3 per second mechanical flushing shaft to 1m^2 corridor window AOV
	12	French system – 2 fan-assisted 'push-pull' smoke shafts (0.1875m^2 extract/0.1125m^2 inlet) (1.5m^3 per second extract shaft and 0.9m^3 per second inlet shaft)
Pressurisation	13	50Pa pressurisation to stairs with stair door into corridor open to 0.1 (hose-line)
	14	50Pa pressurisation to stairs with stair door into corridor fully open (hose-line)

The output data suggests that corridor heat flux to the floor reached 21kW/m^2 in some situations. It has been established that a maximum heat flux at firefighter locations of <5kW/m^2 is an acceptable operational limit for firefighter exposure, while 10kW/m^2 for more than a few seconds may see fire crews facing life-threatening conditions. No account has been made for any firefighting water applications, but it may be the case that such conditions dictate that an immediate evacuation or extraction from the space is needed.

Study findings

The various methods used to provide natural ventilation to common area stairs, corridors and lobbies have evolved over several decades. We are now seeing a move to smaller vents and smoke shafts, in conjunction with fan-assisted systems that work on the principle of creating pressure differentials between the stairs and the corridor. In some cases, a powerful air movement is forced through a corridor and pressure differentials are not dominant, particularly with smoke flushing or dispersal systems based on the 'push-pull' principle.

However, what is important to the designer may conflict with what is important to the firefighter. In general, smoke shafts will assist firefighters in the vast majority of situations, but in a narrow range of circumstances, the operation of a smoke shaft may cause tactical disadvantage and, in rare circumstances, particularly where a compartment fire is grossly under-ventilated, it may enhance or cause unusually rapid fire development.

This study has identified that where compartment fires develop slowly, leading to low-temperature under-ventilated conditions, a remote ignition of the fire gases may occur in the corridor as firefighters gain access to the fire compartment to begin the firefighting phase. This event may create untenable conditions in the corridor for the firefighters, which may be inescapable.

In particular, the naturally vented smoke shafts and exterior wall vents serving corridors may initiate

Table 2: Access to fire compartments

There were 14 base zone models with door entry made at 2,250 seconds (800 seconds with model 1)

1. **Steel container fire behaviour training unit (under-ventilated compartment door entry)**
Although the ignition of fire gases at the corridor ceiling is brief with peak ceiling temperatures of 476°C and 83°C at the floor with a peak heat flux to corridor floor of 6kW/m^2, room pressures in the fire compartment demonstrate typical under-ventilated pulsating patterns.

2. **Baseline unventilated 15m x 1.8m corridor**
Any ignition at the corridor ceiling was so brief (there may have been none) that peak ceiling temperatures of 250°C and peak heat flux to corridor floor is just 2.0kW/m^2. However, there is still a large amount of unburned fire gases remaining in the fire compartment, presenting a danger.

3. **Unventilated corridor with stair 1.0m^2 automatic opening vent (AOV) and door to stairs fully open**
The brief ignition (if any) of gases at the ceiling in the corridor caused temperature peaks of 374°C (upper layer) and 33°C (lower layer) and peak heat flux to corridor floor of just 3.8kW/m^2.

4. **Corridor with stair 1.0m^2 AOV and door to stairs fully open and 1.5m^2 window AOV in corridor open**
The ignition of gases at the ceiling in the corridor caused temperature peaks of 614°C (upper layer) and 96°C (lower layer) and peak heat flux to corridor floor of 15kW/m^2. Corridor pressure dropped to -10Pa, stair pressure dropped to -24Pa.

5. **Single 1.5m^2 window AOV in corridor open**
The opening of a 1.5m^2 AOV window in the corridor leads to a major burn-off of fire gases, lasting over 310 seconds. With corridor temperatures of 633°C in the upper layer and 145°C at the floor, there is a peak 18kW/m^2 heat flux produced.
A corridor pressure of -5Pa continued to draw combustion products out from the fire compartment as an air-flow path was established to the exterior.

6. **Approved Document B 1.5m^2 natural shaft**
170 second flashover in corridor with -105Pa in shaft as it extracts and -68Pa in corridor with ceiling temperature peaking at 747°C and 70°C at the floor, with a peak heat flux to corridor floor of 21kW/m^2.

7. **2 x 750m^2 natural shafts (non code compliant)**
During the extended corridor gas ignition, upper layer temperature exceeded 730°C and peaked at 68°C at the floor, providing a heat flux of 19kW/m^2 to the corridor floor.
Both shafts were demonstrating negative pressures to -115Pa, producing a negative pressure in the corridor of -67Pa.

8. **Mechanical extract 0.65m^2 shaft to 2m^3 per second – with natural make-up shaft**
All leakage air-flow is into corridor as flashover occurs at high level, 577°C at the ceiling and 64°C at the floor results in a peak heat flux to the corridor floor of 10kW/m^2. The two shafts were both extracting as the natural make-up air shaft acted as a chimney causing -42 to -21Pa in corridor, -57Pa in the powered extract shaft and -45Pa in the make-up air shaft (which is extracting). Stair pressure remains around 0Pa.

9. **Mechanical extract 0.5m^2 shaft to 4m^3 per second – make-up air from stairs**
All leakage air-flow is into corridor as flashover occurs at high level, 412°C at the ceiling and 36°C at the floor results in a peak heat flux to the corridor floor of 4.5kW/m^2.
With make-up air coming from the stairs, stair pressure drops from -11 to -3Pa, dropping to -15Pa in the corridor.

10. **2 x 0.75m^2 3m^3 per second mechanical flushing shafts (one is natural extract)**
The two shaft flushing (dilution) system, forcing air down into the corridor at a rate of 3m^3 per second (+64Pa) down the left side shaft, causes +8Pa to -22pa in the natural extract shaft (right side). This creates a +24Pa pressure in the corridor, eventually reducing to +7Pa, with stair pressure reducing to +8Pa. A heat flux of 0.4kW/m^2 at the corridor floor is recorded in the corridor.

11. **1 x 0.75m^2 3m^3 per second mechanical flushing shaft to 1m^2 corridor window AOV**
With the opening of the fire compartment at 2,250 seconds, the automatic flushing shafts force air into the corridor at 3m^3 per second and this exits via the corridor window AOV. Pressure in the corridor is +7Pa and stairs 0Pa. Peak heat flux at the corridor floor is just 0.2kW/m^2.

12. **French system – 2 fan-assisted 'push-pull' smoke shafts (0.1875m^2 extract/0.1125m^2 inlet) (1.5m^3 per second extract shaft and 0.9m^3 per second inlet shaft)**
This system performed well with a maximum upper layer temperature of 88°C and a heat flux at the corridor floor of 0.7kW/m^2. Pressure in the corridor showed -7 to -0.5Pa, with stair pressures around 0Pa.

13. **50Pa pressurisation to stairs with stair door into corridor open to 0.1 (hose-line)**
Another system that achieved effective data with a maximum corridor ceiling temperature of 120°C and a maximum heat flux to the floor of 0.6kW/m^2 – at all times the stair is protected.

14. **50Pa pressurisation to stairs with stair door into corridor fully open (hose-line)**
Another system that achieved effective data with a maximum corridor ceiling temperature of 95°C and a maximum heat flux to the floor of 0.4kW/m^2 – at all times the stair is protected.

Table 3: Model results

The data for all 14 base models shows that naturally vented configurations and fan-assisted depressurisation of the corridor may cause remote ignitions of fire gases as they exit from the fire compartment. The systems modelled in simulations 10-14 demonstrated that conditions in the corridor were likely to be far more tenable for firefighters. The CFAST models of ventilation systems that seemed to offer better protection to firefighters when opening up these grossly under-ventilated scenarios were those that created neutral or positive pressures in the corridor both prior to and after the fire compartment door was opened fully. However, it is also critical to ensure that pressure differentials are configured effectively to protect the stair from smoke infiltration.

	CFAST design scenario (simulation)	Maximum corridor upper layer temperature (°C)	Duration of corridor fire gas burn-off (seconds)	Heat flux to corridor floor (kW/m^2)	Pressure in corridor (Pa)	Pressure in stairs (Pa)
1	Steel container fire behaviour training units (under-ventilated door entries)	476	10	6	+100	n/a
2	Baseline unventilated 15m x 1.8m corridor	206	10	1.2	-0.7	0
3	Unventilated corridor with stair 1.0m^2 automatic opening vent (AOV) and door to stairs fully open at 1,800 seconds	374	20	3.8	-26	-30
4	Corridor with stair 1.0m^2 AOV and door to stairs fully open and 1.5m^2 window in corridor open at 1,800 seconds	614	190	15	-10	-24
5	Single 1.5m^2 window AOV in corridor open	633	310	18	-5	0
6	Approved Document B 1.5m^2 natural shaft	747	170	21	-68	0
7	2 x 750m^2 natural shafts (non code compliant)	735	170	19	-67	0
8	Mechanical extract 0.65m^2 shaft to 2m^3 per second – with natural make-up shaft	577	220	10	-45 to -21Pa	0
9	Mechanical extract 0.5m^2 shaft to 4m^3 per second – make-up air from stairs	412	30	4.5	-42 to -15	-11 to -3
10	2 x 0.75m^2 3m^3 per second mechanical flushing shafts (one is natural extract)	96	0	0.4	+24 to +8	+24 to +7
11	1 x 0.75m^2 3m^3 per second mechanical flushing shaft to 1m^2 corridor window AOV	88	0	0.2	+7	0
12	French system – 2 fan-assisted ‘push-pull’ smoke shafts (0.1875m^2 extract/0.1125m^2 inlet) (1.5m^3 per second extract shaft and 0.9m^3 per second inlet shaft)	160	0	0.7	-7 to -0.5	0
13	50Pa (stair door partially open to 0.1)	120	0	0.6	+5 to +1.4	+55-51
14	50Pa (stair door fully open)	95	0	0.4	+15 to 25 to 11	+54 to 39

unfavourable air-flow paths and excessive depressurisation, ‘pulling’ flaming combustion into the corridor where firefighters are advancing their hose-line. In the case of the automatic opening wall vent located in the corridor (simulation 5), it was notable that a smaller 0.5m^2 vent opening created far less severe conditions in the corridor than the 1.5m^2 opening.

Where fan-assisted systems were modelled (simulations 8-14), it was observed that, while there may be less likelihood of untenable conditions being created in the corridor in comparison to naturally vented scenarios, the systems creating depressurisation of the corridor were less effective in protecting firefighters. The modelling of vent configurations that seemed to offer better protection to firefighters when gaining access to these under-ventilated fires were those that created neutral or slight positive pressures in the corridor, both prior to and after the fire compartment door was opened fully.

The systems that performed most effectively (simulations 13-14), by protecting firefighters in the corridor and ensuring smoke infiltration into the stairs was least likely, was that which provided +50Pa pressurisation to the stairs.

As a result, a key finding of the study is that, for design purposes, the firefighting phase should be addressed from different worst-credible scenarios at the point firefighters are opening the fire compartment to gain access. These should account for two to three rooms post-flashover, as well as a grossly under-ventilated fire.

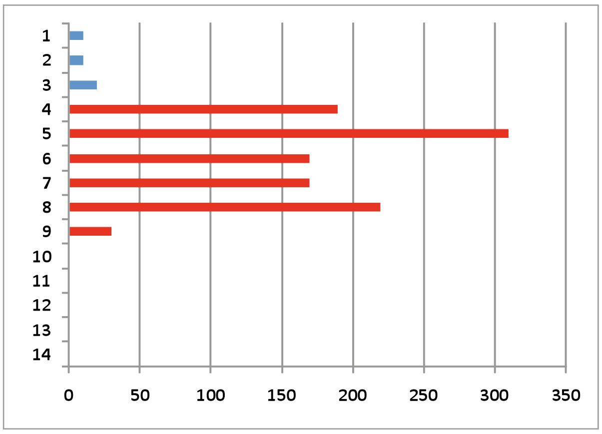


Figure 1: Red zone denotes corridor flashovers in excess of 20 seconds where remote ignitions of the fire gases may present an inescapable environment to firefighters

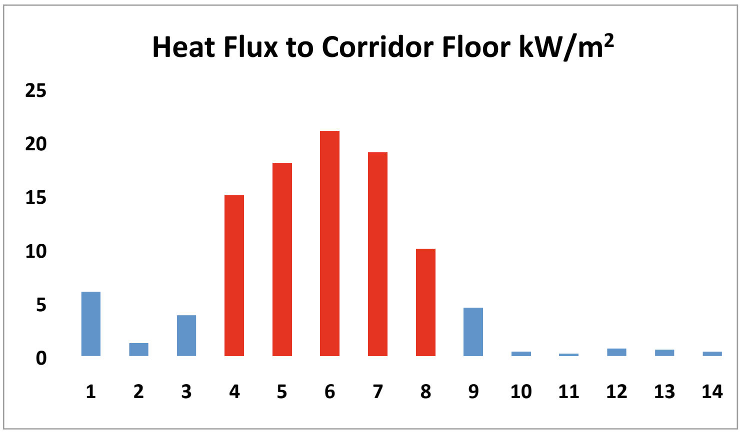
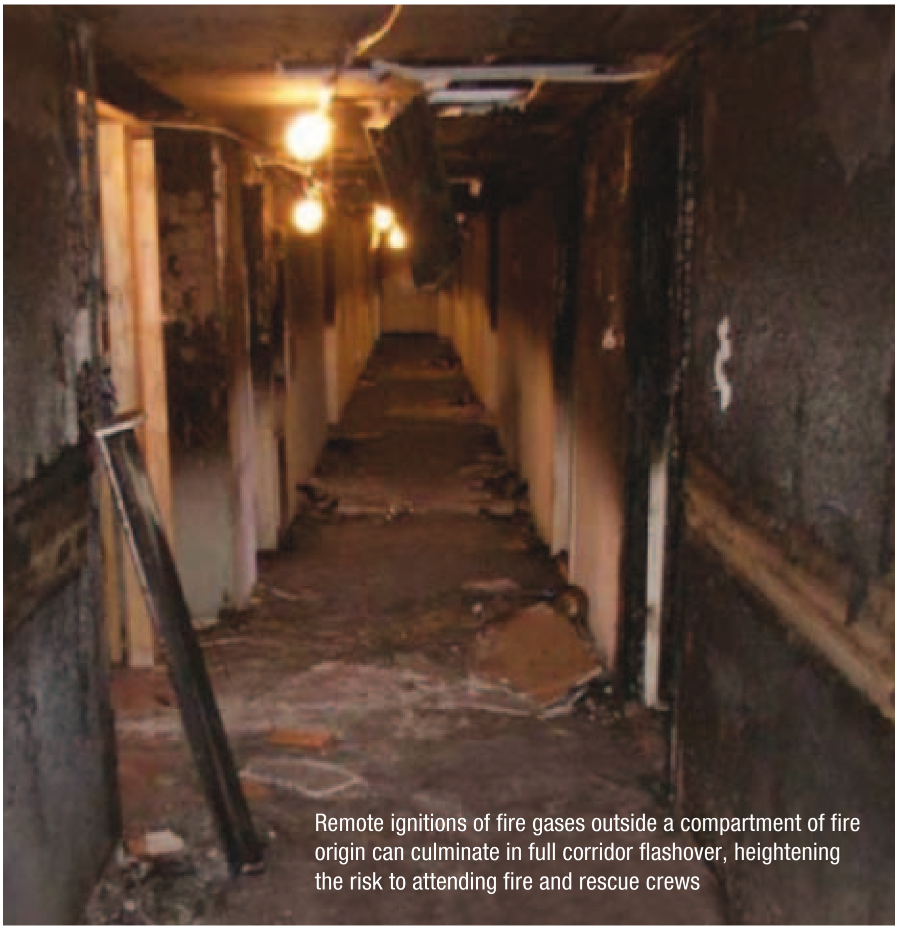


Figure 2: Red zone denotes heat flux to the corridor floor (vertical axis) is at or in excess of 10kW/m^2, which represents dangerous and untenable conditions for firefighters

During the study, a range of airflows, corridor velocities and leakage paths were modelled for each system to analyse how altering various parameters might impact on the duration and intensity of remote ignitions. During this process, over 70 CFAST models were produced. The 15m corridor was also extended to 30m to provide further data. It was noted that the systems that worked to extract smoke generally performed less effectively and remote ignitions occurred on almost every occasion.

The systems that performed well were again those that worked on the principle of flushing the corridor or pressurising the stairs.



Remote ignitions of fire gases outside a compartment of fire origin can culminate in full corridor flashover, heightening the risk to attending fire and rescue crews

Future tactics

It may be that compartment firefighting tactics in buildings where automated or open ventilation paths exist should address these issues. Individual fire and rescue services might consider training firefighters to recognise different types of systems in order for them to take greater control of the ventilation override controls, where conditions dictate.

This study acknowledges the limitations of zone modelling in evaluating the impact of various ventilation configurations on fire development within the compartment of origin and beyond. However, it was noted and agreed from a practical perspective that the results represent typical fire phenomena that may be encountered by firefighters located in the access corridor, and the models therefore appeared fairly accurate in their representation of likely events.

The next stage of the research will undertake full-scale live fire testing that intends to evaluate the impact of various venting configurations on fire development in the access corridors and address pressure differentials at the stair door to see if the stairs remain protected at all times from smoke infiltration ■

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