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A performance based approach to defining and calculating adequate firefighting water using s.8.5 of the design guide BS PD 7974:5:2014 (fire service intervention)

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ABSTRACT

The determination of firefighting water requirements in large, tall and complex buildings in the UK has largely been based on data retrieved from studies into full-scale test fires, combined with some real fire research undertaken by the Fire Research Station (FRS) from 1955–1970. This scientific research effectively formed the basis for the design and configuration of rising fire mains (stand-pipes) in tall buildings, as well as water storage provisions for town centre and infrastructure planning. The resulting guidance is also applied to individually isolated buildings that are distanced from the nearest available water supply. However, it is suggested the UK has since fallen behind many international standards and codes, where firefighting water provisions are more reflective of modern building design as movable fire loads, compartment dimensions and window (ventilation) sizes have increased over the years.

There have been recent calls in both the UK and USA for the development of a performance based method of calculating firefighting water requirements for design purposes, based on the quantity of water actually being used effectively by firefighters. The recent publication of BS PD 7974:5:2014 (7974) meets this need in calculating 'adequate' and effective firefighting water (s.8.5). The research by Glasgow Caledonian University (GCU) provides a framework upon which the '7974' water strategy evolved and is based on an analysis of 5401 building fires that occurred in the UK from 2009 to 2012, where active firefighting was undertaken across a broad range of occupancies. When used in design, any recommended deviations from the prescriptive codes may achieve some cost/benefit advantages, whilst at the same time providing an improved firefighting water flow density (L/min/m^2). It is also worth noting that UK prescriptive building codes do not differentiate between the volume of firefighting water storage required for residential or commercial buildings. Furthermore, reductions in compartment size and fire load, or enhancements to passive/active fire protection, may mean even less storage water is required when using the 7974 strategy compared to current code compliance.

The GCU research clearly established that the severity of building fires is dependent on the size of compartment in which the fire originates; the containment of fire spread through the provisions of adequate passive or active fire protection; the fire load density and the potential for a fire to reach a fuel controlled burning regime at peak heat release for the compartment at Q_{max}. It is further demonstrated that the quantity of firefighting water that may be deemed as 'adequate' can be presented on a gradient (Fig. 13), ranging from the lesser amount (L/min) required in residential buildings (low-flow), upwards through offices or commercial mixed use buildings (mid-flow), to industrial and storage facilities (high-flow). This finding is not reflected in current codes. In using the '7974' methodology to calculate adequate firefighting water, simple equations are utilised in this paper for both sprinkler protected and non-sprinklered occupancies. The method can be also be used where either dry or wet rising fire mains (standpipes) are required.

In referring to past fire case histories it is then demonstrated that fires can travel across large floor plates, with great speed. A spread rate of >20 m^2/min may see a fire develop with such velocity and power that any fire service intervention can become compromised from the outset, unless adequate firefighting water provisions are available and effective fire protection measures are in place.

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1. Introduction

All fire and rescue authorities in the UK are required by law [1], *to take all reasonable measures to ensure the provision of an adequate supply of water in the event of fire and to secure its availability for use in firefighting*. It is further noted that adequate firefighting facilities, adequate hydrants or storage water provisions, and access to buildings must be provided to enable firefighting water to be effectively and promptly deployed.

In general, international design guidance is reflective of firefighting needs in respect of minimum flow-rates (L/min) and maximum hose lay distance (m) from the fire main outlets to the furthest point on a floor plate. However, the flow-rate density (L/min/m^2) of applied firefighting water is rarely something that is considered or prescribed. A performance based approach takes the flow-rate density into account and uses this key measure as a means of providing adequate firefighting water across all parts of a floor plate, whilst maintaining economy in the overall water storage provisions.

The recent publication of BS PD 7974:5:2014 fulfils the need for up-to-date performance based design guidance in meeting the fire service's requirement for an 'adequate' supply of water in large, tall or complex buildings (s.8.5), recently called for in both the UK [2], and USA [3]. However, whilst there is prescriptive guidance [4], in place detailing the required firefighting water provisions, it is logical that any design engineer or building developer is going to ask why the more onerous recommendations in PD 7974 should form a part of any fire design strategy. It is important to realise that the base calculations in 7974 are for non-sprinklered buildings only and reductions in firefighting water can be achieved through the addition of a sprinkler compensatory coefficient to the calculations. Whilst there are several options open to the fire engineer to include a coefficient in the base calculations as compensation for sprinkler protection, this paper offers one such solution. An objective should be to deliver adequate firefighting provisions integrated within an active/passive fire protection and management strategy that remains cost effective. This paper considers how this might be achieved.

What is also important is that the fire service recognise that the design of rising fire mains is according to national standards and that the ability to take full advantage of the firefighting facility, their equipment including pumps, hose lengths and diameters, and branches/nozzles must all be effectively matched with the design standard. If not, then their firefighting capability at height may be severely compromised.

2. The performance based (7974) approach to firefighting water provisions

2.1. Existing prescriptive criteria in the UK

The existing prescriptive criteria in the UK for rising main and water storage provisions in tall buildings above 50 m are shown in Table 1.

The final point (7) suggests that for each additional fire main above 899 m^2 floor area, the additional water required should be considered, based on an 'adequate' provision for the purposes of extinguishing a developing or fully developed fire. A previous UK regulation [5], recommended two fire mains to every 2000 m^2 of floor area and an additional fire main was required after 2000 m^2 for each additional 1500 m^2, or part thereof. So for a 3500 m^2 floor area above 60 m in height, a flow provision of 1.29 L/min/m^2 was required. However, no consideration was given to occupancy type or compartment dimensions and the same provisions were equally applicable to blocks of flats, as well as open-plan office floors.

2.2. Innovative performance based methodology

It is demonstrated in a study of 5401 building fires in the UK from 2009 to 2012, that effective firefighting water provisions are dependent on six main factors:

- Occupancy type (residential fires require far less water than industrial/storage occupancies, or even office buildings)
- Fire load energy density (MJ/m^2)
- Floor area (m^2)
- Existing passive or active fire protection measures
- Potential vent openings and floor space ratios (A_v/A_f)
- An adequate water source

The formulae resulting from the Glasgow Caledonian University (GCU) research for non-sprinklered buildings are included in BS PD 7974:5:2014 [6], and can be used to calculate the required flow (L/min) for various occupancies based on the above six factors, as follows:

Eqs. (1)–(3) utilise occupancy type and floor area (m^2) inputs whereas Eq. (4) incorporates fire load density (MJ/m^2), which can also be applied to high-stacked fire loads (Eq. (4a))

The formulae resulting from the Glasgow Caledonian University (GCU) research for non-sprinklered buildings are included in BS PD 7974:5:2014 [6], and can be used to calculate the required flow (L/min) for various occupancies based on the above six factors, as follows:

Eqs. 1–3 utilise occupancy type and floor area (m^2) inputs whereas Eq. 4 incorporates fire load density (MJ/m^2), which can also be applied to high-stacked fire loads (Eq. (4a)).

For fires in non-sprinklered dwellings (house, flats, maisonettes and apartments)

$$F_{\mathrm{dwe}} = 75 * A_{\mathrm{fire}}{}^{0.44} \tag{1}$$

For fires in non-sprinklered factories, industrial units and storage warehouses

$$F_{ind} = 131 * A_{\mathrm{fire}}{}^{0.51} \tag{2}$$

Table 1
Prescriptive requirements for rising fire mains and firefighting water storage in the UK.

1	Fire mains should have a minimum nominal bore of 100 mm and the system should be designed to withstand a pressure of one and half times its predicted maximum operating pressure(BS 9990:2015).
2	At least two wet-rising fire mains are to be provided where floor area exceeds 899 m^2. (Building Regulations Part B)
3	A minimum flow-rate from each riser of 1.67 L/min/m^2 (1500/899 m^2) must be achievable (BS 9990:2015 and BR part B).
4	A maximum hose-lay distance (45 or 60 m) is stipulated from each fire main, according to BS 9999:2008 and BS 9991:2011.
5	Where the mains supply of firefighting water fails to meet a flow of 1500 L/min to all floors, a combined water storage facility/mains tank fill, capable of meeting the firefighting flow requirement for 45 min, is required (Totalling 67,000 l) (BR part B).
6	Pressure-reducing valves should be provided to regulate the flow and pressure to (750 ± 75) L/min at (8 ± 0.5) bar per outlet (BS 9990:2015).
7	Where more than one fire main is installed in a building, the potential need for additional water storage and/or pumping capacity should be taken into account (BR part B).

For fires in non-sprinklered public, office, commercial, schools, hospitals, hotels and smaller industrial buildings (based on research by Sardqvist into 307 fires in London)[1]

$$F_{other} = 61 * A_{fire}^{\ 0.57} \quad (3)$$

where

F_{dwe}; deployed flow-rate (L/min) for dwellings
F_{ind}; deployed flow-rate (L/min) for factories, industrial and storage warehouses
F_{other}; deployed flow-rate (L/min) for 'all other' buildings (Sardqvist)
A_{fire}; maximum predicted fire area (m^2)

Or alternatively using the estimated fire load energy density (MJ/m^2) for all building occupancies, from BS PD 7974:5:2014:

$$F_{design} = 0.00741 * \left(q_k * A_f \right)^{0.666} \quad (4)$$

Or for high-stacked fire loads (retail; industrial or storage etc)

$$F_{design} = 0.\ 00741 * \left(\left(q_k * h \right) * A_f \right)^{0.666} \quad (4a)$$

where

F_{design}; design flow-rate for a fully involved fire compartment burning at maximum intensity at Q_{max} (L/s)
q_k; fire load energy density for the compartment (MJ/m^2), also taking height of the fire load into account for vertical load stacks.
A_f; total internal floor area of the protected compartment (m^2)
h; height of stacked storage (m)

In the Glasgow Caledonian University (GCU) research used to form the methodology in 7974:5, the following benchmarks were demonstrated for developing fires in non-sprinklered compartments:

a. *Critical* flow-rates, below which a developing fire is unlikely to be controlled.
b. *Minimum* flow-rates where suppression is achievable but firefighters face severe and punishing conditions.
c. *Optimum* (adequate) flow-rates where control of the fire is achievable without unnecessary punishment to firefighters.

Critical flow-rate; 2.0 L/min/m^2
Minimum flow-rate; 3.7 L/min/m^2
Optimum (adequate) flow-rate; 6.0 L/min/m^2 (two dwelling rooms totalling 32 m^2), 6.5 L/min/m^2 (commercial 50–100 m^2), 0.407L/s/MW (Grimwood), and 0.385L/s/MW (Barnett)

The formula outputs throughout this paper fall into an acceptable upper quartile, where proposed flow-rates for growth stage fires never fall below the CFR and in most cases (> 80%), meet the optimum flow rate (adequate water). As building fires spread beyond control, the required flow-rate density (L/min/m^2) (applied defensively into decay stage fires) is greatly reduced. The uncertainties of coefficients used in the formulae are also addressed with an error of margin set at 10%.

There are global benchmarks that can also be used to determine the amount of firefighting water that is required to extinguish real fires in tall buildings and these have influenced international building codes when designing rising fire main installations and water storage provisions in support.

What is currently used in the UK, is a prescriptive wet rising fire main design specification, based on small residential sized compartments, which would fail to meet most international standards for tall buildings where commercial or mixed use buildings are concerned.

2.3. Sprinkler protected buildings

The calculations provided above, and in BS PD 7974:5:2014, do not take into account a sprinkler controlled fire. Where sprinklers are installed according to relevant design standards a compensatory coefficient should be included in the equations. There are several methods open to the fire engineer to account for sprinklers in the calculation process that will reduce firefighting water storage and supply provisions.

One of the most common designs for tall office buildings is based around a central or offset core housing lifts, stairs and services. The core of the building generally occupies 15–25% of the overall floor-plate, so a typical floor area of 3000 m^2 might consist of a 750 m^2 central core and a 2250 m^2 open-plan office floor plate. With this design there should be maximum hoselays from the centre of the core to the corners of the floor of around 40 m.

As an example, NFPA 14 [8], accounts for a reduced supply of firefighting water for sprinklered buildings by reducing the rising fire main (standpipe) and water storage requirements by 20 percent. It is proposed here that reductions of up to 40% in flow-rate density provisions and water storage may be achievable when meeting a risk assessed management strategy, based on a stringent points scale [9]. In doing so, a 40% (maximum) reduction is achievable only in situations where the fire service are able to demonstrate that an early intervention is likely to succeed before the fire spreads to a level considered beyond control of manual fire suppression efforts.

As an example (Table 2), by adding a 0.7 coefficient to the calculations we can account for a 30% sprinkler reduction in the following way:

$$F_{other} = 61 * 2250^{0.57} * 0.\ 7 = 3477\ L/\ min$$

$$F_{design} = 0.00741 * (570 * 2250)^{0.666} * 0.7 = 3639\ L/\ min$$

In each case the optimum practical design solution is to provide two 150 mm rising fire mains, each with at least two outlets per floor, providing a minimum total flow-rate of 3500 L/min. Using the above method for a sprinkler protected environment provides a minimum flow density of 1.55 L/min/m^2, which is considered a reasonable flow-rate for a sprinkler protected open-plan office floor plate meeting a risk-assessed points scale system (Fig. 1).

Equally, a 20% sprinkler coefficient might be used when calculating fire protection for high-rise flats or 100 m^2 apartments as follows:

$$F_{dwe} = 75 * 100^{0.44} * 0.\ 7 = 456\ L/min$$

So for sprinkler protected 100 m^2 apartments, two hose-lines flowing 456 L/min (one as a safety line as needed in high-rise) would be adequate. Therefore the engineered flow provision is rounded to 1000 L/min, with a much reduced water storage requirement in buildings > 30 m in height, compared to a code compliant provision.

2.4. Water storage provisions (performance based)

The amount of water required to extinguish a compartment fire varies between occupancy types and purpose groups [10]. However current UK prescriptive building codes fail to differentiate between the amounts of water needed for the suppression of fires

[1] Särdqvists [7], Eq. (3) forms part of the GCU research although it does not appear in PD 7974/5.

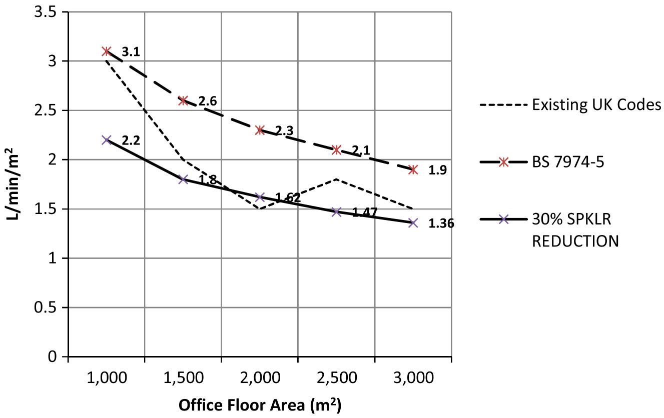

Fig. 1. A comparison of flow-rate density provisions across occupied floor space, between prescriptive UK regulations and the performance based BS PD 7974:5:2014 (excluding core areas) where a 30% sprinkler reduction has been applied.

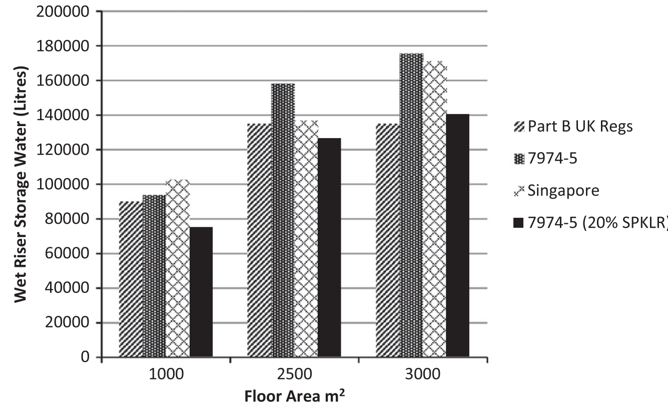

Fig. 2. The required or proposed water storage for wet rising fire main installations serving offices, providing 30 min continuous firefighting provision. An additional requirement for fire service connections to enable pumpers to augment the supply and maintain the flow-rate is also generally applied.

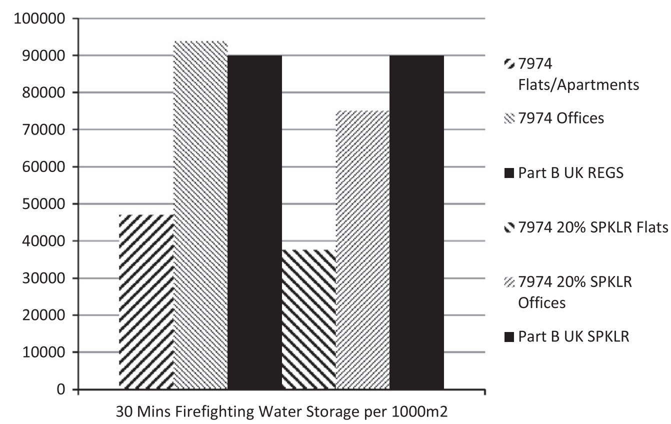

Fig. 3. A comparison (from left to right) of water storage requirements for a 30 min supply, between flats and offices using the BS PD 7974-5 methodology as opposed to the ADB approach where firefighting water provisions are the same for all building occupancies (providing maximum 45 m hose-run distances are achieved).

across the diverse range of buildings and this reflects directly on the amounts of water recommended for storage water. The prescriptive requirement (UK Building Regulations part B) is generally for 45,000 l in storage water per fire main, supplemented by a further 22,000 l in tall buildings provided by fire service connections augmented into the storage facility from street hydrants. This enables a continuous firefighting water flow-rate of 1500 L/min for a period of 45 min.

In most countries, including the USA and Singapore, a 30 min firefighting water storage provision is normally acceptable. However, this is only where wet riser water storage facilities can be promptly and effectively augmented by fire service pumpers in order to maintain the required flow-rate beyond the initial 30 min duration. As large office floor plates can burn for 120 min and beyond, fire service connections play a critical part in ensuring an adequate and ongoing water provision.

The performance based 7974 approach enables cost savings to be made, but not at the expense of a reduced flow density (L/min/m^2). In general, most buildings above a certain height are required to have sprinkler coverage as well as wet risers, the sprinkler coefficient will allow less storage water but the provision of 150 mm rising mains, with at least two outlets per main per floor, will ensure adequate flow density is achieved with less hose, which is very important to firefighters (Figs. 2 and 3).

An isolated building located some distance from a water source is another example where a balance may be drawn between the provision of sprinklers (and associated water storage) against a bespoke firefighting water storage facility. A 200 m^2 dwelling might consider a 30 min firefighting water storage facility to support fire service intervention, as an alternative to installing sprinklers; where for dwellings

$$F_{dwe} = 75{*}200^{\,0.44} \text{ using Eq. (1)}$$
$$= 772 \text{ L/min} \times 30 \text{ min} = 23,160 \; l$$

3. Travelling fire spread across large open-plan floor space

3.1. Floor space efficiency in tall buildings

The relationship between cost benefit and safety is a critical part of any design for large, tall or complex buildings. It is

Table 2
A comparison of flow-rate density provisions across occupied floor space, between prescriptive UK regulations and the performance based BS PD 7974:5:2014 (excluding core areas).

Maximum fire-resistingCompartment Floor Area (m^2)	Flow-rate L/min/m^{2}Existing UK Prescriptive Codes	Flow-rate L/min/m^{2}BS PD 7974:5:2014Performance based without sprinklers	Flow-rate L/min/m^{2}BS PD 7974:5:2014 Performance based with 30% sprinkler reduction
250	6	5.7	4.0
500	3	4.2	3.0
899	1.7	3.3	2.3
1500	2.0	2.6	1.8
2000	1.5	2.3	1.6
2500	1.8	2.1	1.5
3000	1.5	1.9	1.4

becoming common to see multi-occupancy buildings with offices, hotels, apartments, restaurants and retail complexes together in one building. Where commercial space is involved we often see large open-plan areas with floor to ceiling glass and high fire load densities spaced evenly across the floor plate. In large metropolitan cities it is commonplace to see a central core design in very tall buildings with accommodation space sited around centrally located lifts, stairs and service shafts. Space efficiency is broadly defined as the ratio of 'net to gross floor area' (NFA to GFA). The space efficiency, as well as the shape and geometry of the high-rise building need to satisfy the value and cost of the development equation. Typical open-plan floor plates may range anywhere between 1000 and 3000 m^2 with NFA to GFA ratios of 70–85% (the central or peripheral core takes up around 15–30% of the total floor area). It is also common to see lease spans, (the distance of the usable area between the exterior wall and the core, or the multi-tenant corridor) ranging anywhere between seven and twenty metres, although one new building in the city of London reaches out 45 m from the core. However lease spans depend on the regulated functional requirements and are also closely related to the structural frame design and the materials used in construction.

3.2. Fire spread rates on open-plan office floors

When considering firefighting water provisions for the upper floors of non-sprinklered commercial buildings it is important to consider how a developing fire might travel at great speed across large open-plan floor space. A review of fires in large open-plan compartments reveals that in general, these fires do not conform to normal flashover fire development involving the entire enclosure at one time. Instead, these fires tend to move across floor plates, reaching peak levels of heat releases across a limited or zoned area at any one time. These fires have been labelled travelling fires [11], and in some texts this process of fire development has been referred to as progressive burning [12].

This type of fire spread has been observed and recorded many times around the world and testimony by on-scene firefighters will confirm just how rapid fire spread is likely to be in both open-plan and cellular floor layouts. The 't-squared' fire growth rate so often associated with office space is that of 'medium' growth and design codes and standards broadly reflect this. However, where modern open-plan layouts exist a 'fast' growth rate may appear more appropriate (Table 3).

Where a fire is spreading across a large open-plan office floor, it may eventually appear that the entire floor-plate is burning. However, the fire will likely be at different levels of intensity. In some areas the fire may still be in its growth stages whilst elsewhere on the floor-plate the fire may have reached its peak intensity burning at steady state, with other areas burning into the decay stages.

A fire involving an open-plan 1400 m^2 office floor plate located around a central core with narrow floor spans is more likely to demonstrate peak heat release rates across three zones of 470 m^2 or four zones of 353 m^2, depending on fuel distribution and ventilation parameters. The concept of travelling fire spread makes reference to Alpert's ceiling jet correlations and burning time calculations [13], .

Table 3
Fire growth and travelling fire spread rates observed at past high-rise incidents.

High-rise officeBuilding Fire	Initial fire floor area (m^2)	Fire spread (m^2/min)	*t*-squared fire growth rate
Interstate Bank, Los Angeles 1988	1400 m^2 Open-plan offices	22.2	Fast
Windsor Tower Madrid 2005	900 m^2 Cellular offices	7–15	Medium
CCAB Building Chicago 2003	240 m^2 Open-plan offices	20.0	Fast

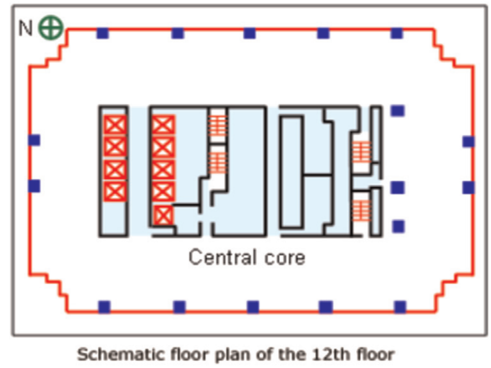

Fig. 4. Plan of the 12th floor at the First Interstate Bank 1988 [14],

3.3. Case history – interstate bank fire in Los Angeles 1988

A good example of travelling fire spread across large open-plan office floor space occurred in Los Angeles in 1988 at the First Interstate Bank building fire. The author visited the site of the fire a few weeks after it occurred and interviewed LA City fire chiefs and firefighters who fought the fire and observed the fire development, over time, on video (Fig. 4).

The tower has a structural steel frame with lightweight concrete slab on profiled steel deck. The external cladding system consisted of glass and aluminium. The fire started in an office area on floor 12 of the 62 storey office tower at 2225 hours and spread up to floor 16 before it was brought under control by the fire service some four hours later. An automatic sprinkler system, although installed, had been shut down awaiting installation of water flow alarms. This analysis is of the fire spread on floor 12 where the fire originated. The open-plan office floor space was located around a large central core that contained lifts, stairs and service shafts. The office space surrounding the core measured 188 m with a 7.5 m span, totalling 1410 m^2.

This analysis looks at the actual spread of fire across the floor plate as recorded in real time (video) and utilises the actual amounts of ventilation available on the fire floor as windows were seen to fail at various locations and times. The fire itself took 65 min to wrap around the core and involve all the available open-plan floor space. Although a 'medium' t^2 fire growth curve is normally applied to office accommodation, the growth stages in this fire very soon developed a 'fast' rate of growth, spreading through 22 m^2 of floor space per minute. The fire has been analysed here (Table 4) using three and four zone models to represent how a travelling fire could spread across the floor plate, demonstrating near field and far field temperatures that may impact on structural elements in a way not accounted for in current codes or standards. To evaluate the requirements for 'adequate' firefighting water, the energy release has been calculated in the 3 and 4 zone models as the entire compartment does not burn to maximum energy release at any one time. In both models there are only brief periods of burning where two zones are burning at Q_{max} at the same time.

As the fire developed, a sufficient number of windows were broken by heat to enable the fire to burn in a fuel controlled state throughout the entire duration of the fire, with 25% A_v/A_f vent

Table 4
Travelling fire analysis at the First Interstate Bank Fire in 1988 (Firesys) [15].

First Interstate Bank Fire12th floor analysis	3 Zone fire	4 Zone fire	Entire 12th floor
Floor Area (m^2)	470	353	1410
Heat of combustion (MJ/kg)	20	20	20
Fire load energy density MJ/m^2	570	570	570
Estimated fire load (kg)	13,253	10,046	40,185
Fire growth rate	Fast	Fast	Fast
Ventilation or fuel controlled	Fuel	Fuel	Fuel
Ventilation opening ratio (%)	25	25	25
Maximum burning rate (kg/s)	5.2	4.3	10.9
Zonal Q_{max} (MW)	104	86	218
Time to uncontrolled burnout (t) (min)	160	154	185
Time to extinguish (Fire Service) (min)	124	124	124

opening to involved floor space ratios fairly constant. Had the fire floor been modelled as a single compartment fully involved in fire the estimated energy release, without suppression activity, would have been around 218 MW, based on a fire load energy density of 570 MJ/m^2 burning at 154 kW/m^2. When modelled as a travelling fire advancing through three zonal areas of floor space the peak energy release (Q_{max}) in each zone is estimated at 104 MW, although there remains an element of additional heat release in adjacent zone as they pre-heat in growth or cool in decay in the far field zones. However, from a firefighting approach, Q_{max} can be used on a zonal basis to calculate the required water flow-rate.

At the Interstate Bank Los Angeles firefighters were unable to deploy adequate water until 34 min into the fire due to a delay in calling the fire department and ineffective fire pump settings serving the wet rising fire mains (standpipes). At this point two thirds of the 12th floor was fully involved in fire although on a zonal basis, part of the floor space would be in decay. Even so, as the firefighters reached the 12th level at 21 min into the fires 'fast' growth rate, any attempt at intervention would have been unlikely to succeed as the fire had already spread to a quarter of the floor plate with an estimated heat release of 86 MW (Figs. 5–8).

3.4. Adequate water calculations – interstate bank fire in Los Angeles 1988

The design flow-rate for the 1410 m^2 open-plan office floor space at the building is calculated using Eq. (4) or Eq. (3) as follows:

$$F_{design} = 0.00741*(570*1410)^{0.666} = 3808 \text{ l/ min}$$

$$F_{other} = 61*1410^{0.57} = 3805 \text{ L/ min}$$

If applying a travelling fire analysis to estimate firefighting water demands it would be necessary to calculate as follows:

- *3 Zone model:*

465 m^2 fire area at 104 MW Q_{max}

$$F_{other} = 61*465^{0.57} = 2,022 \text{ L/ min}$$

Added to this will be a requirement to deal with adjacent zones, mostly during decay stage burning, where 2 L/min/m^2 (critical flow-rate) may be generically applied as follows.

Two additional zones of 465 m^2 totalling a potential 930 m^2 of decay stage burning leading to an additional requirement of $930 \times 2 = 1860$ L/min

Total flow required:$2022 + 1860 = 3882$ L/min

- *4 Zone model:*

353 m^2 fire area at 86 MW $Q_{max.}$

$$F_{other} = 61*353^{0.57} = 1,728 \text{ l/ min}$$

Added to this will be a requirement to deal with adjacent zones, mostly during decay stage burning, where 2 L/min/m^2 (critical flow-rate) may be generically applied as follows

Three additional zones of 353 m^2 totalling a potential 1059 m^2 of decay stage burning leading to an additional requirement of $1059 \times 2 = 2118$ L/min

Total flow required:$1728 + 2118 = 3846$ L/min

3.5. Summary – Interstate Bank fire 1988 in Los Angeles

With fire spreading at a 'fast' t^2 rate across the 12th floor as firefighters arrived on-scene and deployed to the 12 floor, an effective attack on the fire was initially unlikely due to the energy release at this point. As the fire progressed, between five and eight 500 L/min fire streams (some were subsequently redeployed to upper floors as the fire began to spread vertically) totalling 2500–4000 L/min (1.8–2.8 L/min/m^2) were deployed internally on the 12th floor as the fire progressed into its decay stages (totalling 9000 L/min to all fire involved floors from four 150 mm fire main stand-pipes, spaced to cover 353 m^2 of floor space each) (Table 5). To ensure this water continued to flow, firefighters were relieved at approximately 15 min intervals on each hose-line.

Using Eq. (5) [16], the time to effectively extinguish a fully involved fire on floor 12 can be estimated as follows:

$$t_{ext} = 3.3*\sqrt{1,410} = 124 \text{ min} \quad (5)$$

At the Interstate Bank fire the water was actually flowing for just over 120 min on floor 12 before the fire was finally extinguished and the remaining fires up to floor 16 were controlled within 4hours from time of arrival. It is estimated that uncontrolled burning would have exceeded 165 min on the 12th floor. During such a period, the structural elements and steel frame connections would have been subjected to an extended cooling phase, with an increased potential for failure.

3.6. Case history – Windsor tower fire, Madrid 2005

The Windsor Tower or Torre Windsor (officially known as Edificio Windsor in Madrid, Spain) was a 32-storey concrete office building with a reinforced concrete central core. The building was subjected to a three year refurbishment programme when the fire broke out. This refurbishment included the installations of:

- Fire protection to the perimeter steel columns using a boarding system
- Fire protection to the internal steel beams using a spray protection
- A sprinkler system (not operative at time of fire)
- A new aluminium cladding system

Around midnight, on February 12, 2005, a fire was detected in an office on the 21st floor. The fire spread quickly throughout the entire building, leading to the collapse of the outermost, steel parts of the upper floors; firefighters needed almost 24 hours to extinguish it. The fire is estimated to have broke out on the 21st floor, in office 2109 at approximately 23:05 h [17]. Detection occurred at 23:08 h; and a '50 cm flame' was reported to have been seen there at 23:18 h by night staff investigating the alarm. This is consistent with a waste-paper basket fire or similar source. The fire service was called at 23:21 hrs. It was further estimated that the fire on the 21st floor demonstrated a t-squared growth curve from 23:20 h to 00:20 h by which time the fire on that level was

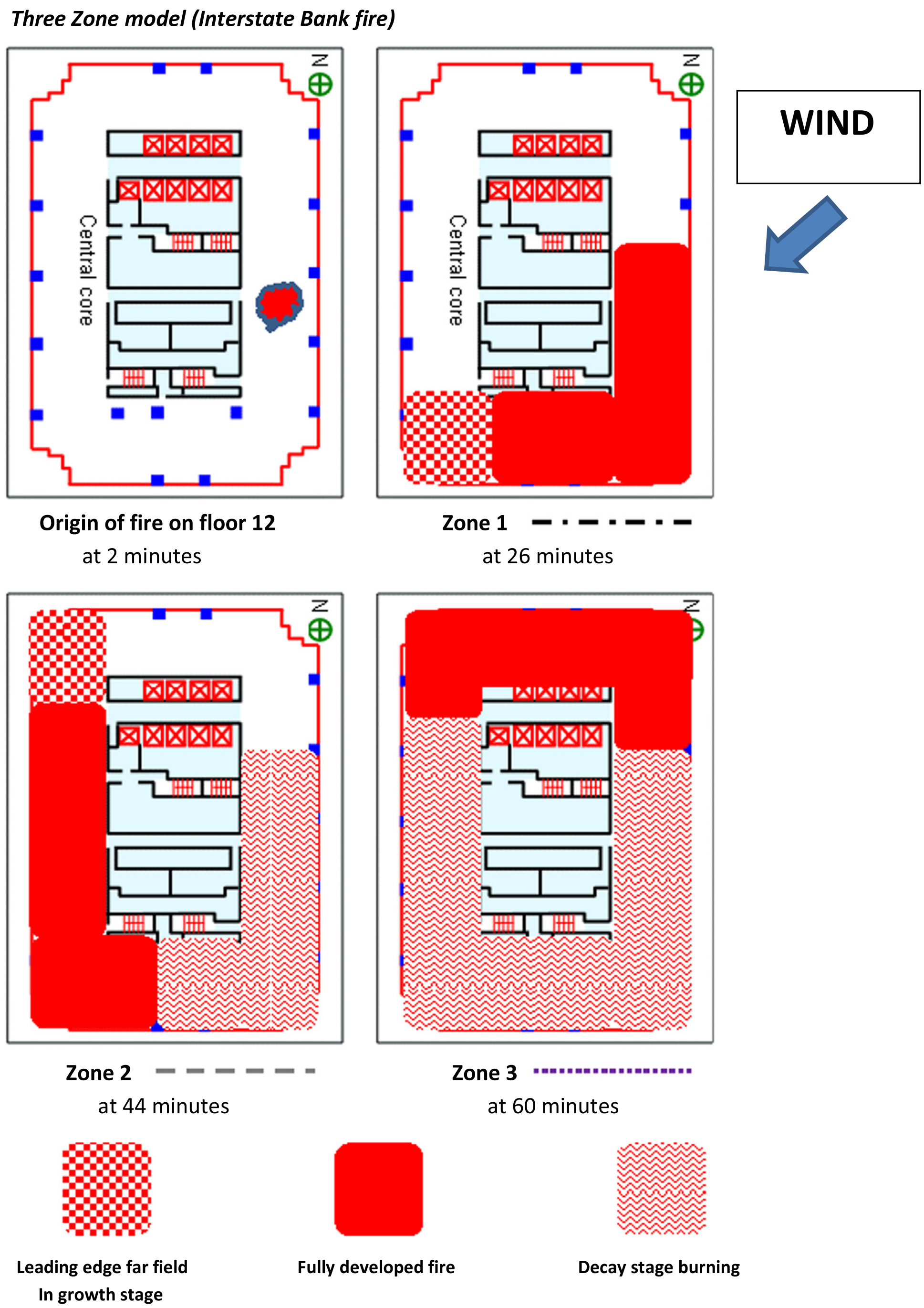

Fig. 5. Three-zone model for uncontrolled travelling fire spread (clockwise) at the Interstate Bank fire 1988; Adapted from an original at the *University of Manchester (school of Structural Fire Engineering) online 'one stop shop'* [13].

transitioning into a decay phase of burning, but further spreading to floors above and below. During this initial fire attack on the 21st floor, several firefighters became caught in an interior collapse of ceiling framework and were rescued by colleagues, suffering varying amounts of heat exhaustion in the process. This allowed the fire to spread unchecked for a short time (Fig. 9 and Table 6).

3.7. Adequate water calculations – Windsor tower fire, Madrid 2005

The design flow-rate for the 911 m^2 cellular office floor space at the building is calculated using Eq. (4) or Eq. (3) as follows:

$$F_{design} = 0.00741*(570*911)^{0.666} = 2847 \ \text{L/ min}$$

$$F_{other} = 61*911^{0.57} = 2967 \ \text{L/ min}$$

If applying a travelling fire analysis to estimate firefighting water demands it would be necessary to calculate as follows:

- ***3. Zone model:***

304 m^2 fire area at 49.3 MW Q_{max}

$$F_{other} = 61*304^{0.57} = 1587 \ \text{l/ min}$$

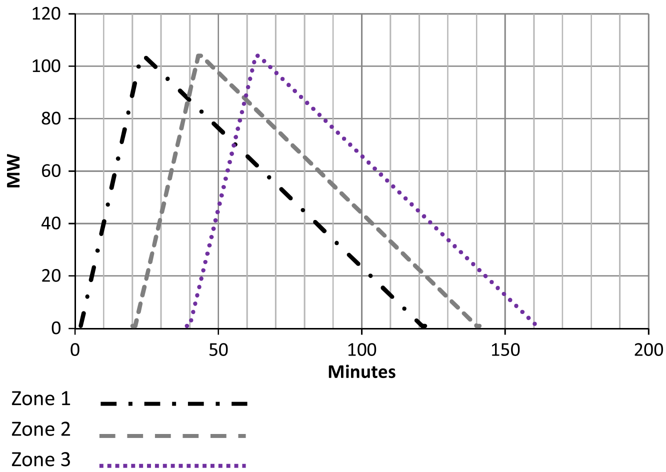

Fig. 6. Three zone model of heat release rates on the 12th floor at the First Interstate Bank 1988.

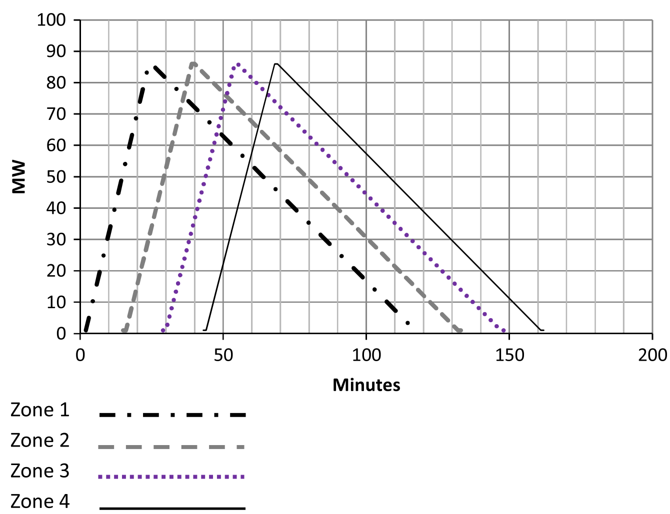

Fig. 7. Four-zone model of heat-release rates on the 12th floor at the First Interstate Bank fire 1988.

Added to this will be a requirement to deal with adjacent zones, mostly during decay stage burning, where 2 L/min/m^2 (critical flow-rate) may be generically applied as follows –

Two additional zones of 304 m^2 totalling a potential 608 m^2 of decay stage burning leading to an additional requirement of $608 \times 2 = 1216$ L/min

Total flow required: 1587+ 1216= 2803 L/min

3.8. Summary – Windsor tower fire, Madrid 2005

With fire spreading across the 21st floor as firefighters arrived at the building, an attack on the fire was initially ineffective due to the increasing energy release at this point and the low pressures and flow available from the rising main. As the fire progressed, between four and six fire streams, flowing an estimated total of 2000 L/min, were deployed into the 21st floor as the fire began to spread vertically. However, the structural integrity began to fail and crews were evacuated from all floors, prior to the building suffering a catastrophic collapse.

4. Firefighting tactics

4.1. Several major high-rise office fires in the UK

Several major high-rise fires have occurred over recent years in the UK where the fire service were unable to extract adequate water from the 100 mm rising fire mains and had to lay additional hose-lines up stairways to extinguish fires in open-plan office buildings. This delay caused the fires to spread to upper floors in all cases.

The fire at Villiers House in the Strand, in 1979, required 40 pumps and 200 London firefighters to extinguish a fire that spread quickly to involve five floors. Then in 1991 a serious fire in the 15 storey steel framed Churchill Plaza office building in Basingstoke [20], caused Hampshire firefighters problems. On arrival they could see the fire through the glass curtain wall but were unable to determine at what level the fire was raging on an open-plan office floor. The large 2000 m^2 floor-plate was shaped as a 'V' with three stairs, one at each end (east and west) and one at the central core of the building. As the fire was reported to be on the 9th floor by security personnel firefighters took the lift directly to that floor and deployed two 45 mm hose-lines from the east stairs. On making their way across the entire smoke laden floor-plate to the west stairs they discovered the fire was actually below them on the 8th floor. The west stair was pressurised but had no rising fire main so they continued to extend one 45 mm line down the west stair, into the 8th floor, which entailed a 175 m hose-lay. Despite a direct attack on the fire, the flow-rate was estimated to be less than 150 L/min and by the time the water was applied the fire had developed to a stage beyond the capability of the hose-line in use. At a point in time, 50 min after the first emergency call to the fire service, the windows on the fire floor failed and an exterior wind caused the fire to escalate dramatically, spreading to involve three upper floors and requiring 200 firefighters to extinguish the fire over a 41/2 hour period.

Another large building fire spread through five floors of open-plan offices in London's west end district in 2003. The thirteen-storey Telstar House was a steel framed concrete building measuring 50×30 m (1500 m^2). With a stair at each end the building was typical of 1960 s design. As like the Churchill Plaza fire, the fire could be seen from the exterior on fire service arrival but the windows had not yet failed. A single work station was involved in fire at the time firefighters deployed an attack using a small first aid hose-line but the low flow-rate (<100 L/min) had no effect on the fire. A second crew were then deployed with a 350 L/min 45 mm hose-line but by this time the fire was spreading rapidly to involve several workstations and the crew suffered heat exhaustion, before being pulled to safety by colleagues. The fire escalated and spread through five floors before being extinguished. A London Fire Brigade Deputy Assistant Commissioner [21], (DAC) reported that the single 100 mm rising fire main installed in the building was totally inadequate in providing the necessary amount of water needed to extinguish the fire and heavy exterior streams were deployed to gain some control. The London DAC stated that a primary flow-rate of at least 900–1000 L/min would have been needed to enable firefighters to attack the fire effectively from the protection of the stair enclosure and that >3000 L/min was subsequently required.

4.2. Tactical learning points from the above fires

- As 100 mm rising mains in the Villiers House; Churchill Plaza and Telstar House fires were too small to provide adequate firefighting water, firefighters were forced to lay additional hose-lines by hand up the stairs and also resort to external

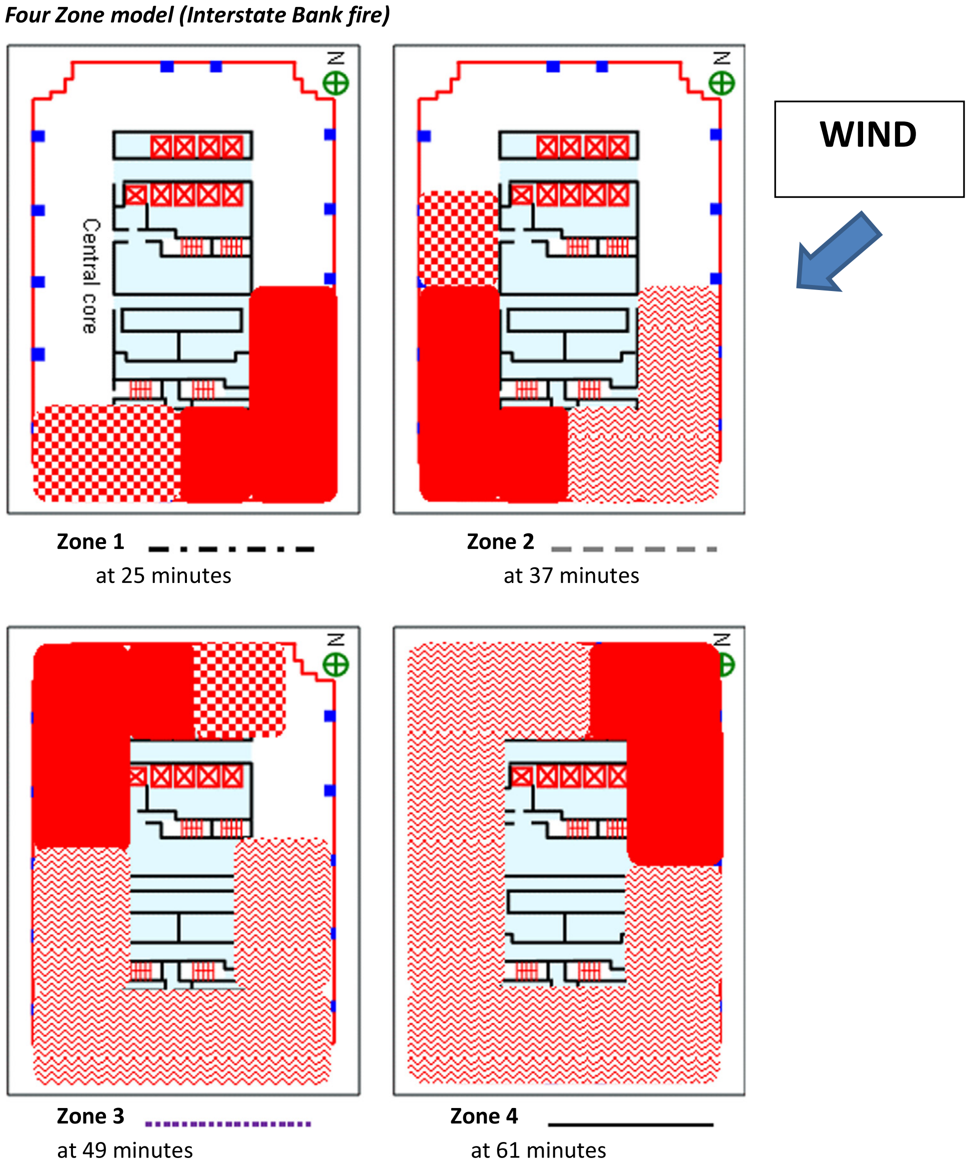

Fig. 8. Four-zone model for uncontrolled travelling fire spread (clockwise) at the Interstate Bank fire 1988; Adapted from an original at *University of Manchester (school of Structural Fire Engineering) online 'one stop shop'* [13].

Table 5
Summary of actual fire flows matched against BS PD 7974:5:2015 design estimates for horizontal fire spread on the 12th floor at the Interstate Bank Fire in Los Angeles, 1988.

Method	Floor space (m^2)	Flow-rate (L/min)	Flow density (L/min/m^2)
One zone model Eq. (4)	1410	3808	2.7
One zone model Eq. (3)	1410	3805	2.7
Three zone model Eq. (3)	3 × 465	3882	2.7
Four zone model Eq. (3)	4 × 353	3846	2.7
Actual Fire	1410	2500–4000	1.8–2.8

attacks. This placed additional resource burdens on the fire service.

- The provision of larger diameter rising fire mains would allow firefighters to lay more than one attack hose-line per floor and apply adequate water onto the fire faster.
- The use of stair protection (fire resisting enclosure) can be a great aid in mounting and maintaining an effective firefighting operation, where fire develops rapidly across large open-plan floor-plates.
- The 'donut effect' where fire wraps around the central core [22], causes firefighters to 'chase' the fire from the burned side, unless adequate facilities and access points are available at both sides of the central core to enable a fire attack to occur from the unburned side.
- Once windows fail, the increase in ventilation will intensify a fire's transition from a medium to a fast growth rate, across

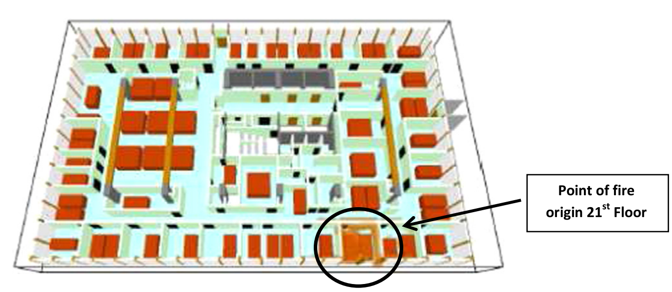

Fig. 9. Plan of the 21st floor at the Windsor Tower showing the point of fire ignition [19].

Table 6
Travelling fire analysis at the Windsor Tower Fire in 2005 [18].

Windsor Tower Madrid21st Floor analysis	3 Zone fire	Entire 21st floor
Floor Area (m^2)	304	911
Heat of combustion (MJ/kg)	20	20
Fire load energy density MJ/m^2	570	570
Estimated fire load (kg)	8653	25,958
Fire growth rate	Med-Fast	Med-Fast
Ventilation or fuel controlled	Fuel	Fuel
Ventilation opening ratio (%)	6	6
Maximum burning rate (kg/s)	2.5	5.1
Zonal Q_{max} (MW)	49.3	102.5
Time to uncontrolled burnout (t) (min)	175	253
Time to extinguish (Fire Service) (min)	N/A	N/A

open-plan floor plates. Additionally, where an exterior wind enters these windows at high velocity the fire may develop at ultra-fast growth rates.

- The early and prompt placement of attack hose-lines flowing adequate water are critical to the success of any firefighting operation of this nature.
- Firefighters must be relieved at 10–15 min intervals to enable the fire attack to continue safely and effectively, as heat build-up between the floor plates is untenable for longer durations. The demand on adequate resources and staffing
- Standard compartment firefighting techniques, applying pulsed sprays or water-fog applications using low-flow nozzles, are ineffective where there is potential for high fire spread rates (to 22 m^2/min) in large compartments.
- High energy fires of this nature demand high-flow hose-lines that are able to penetrate the fuel-base fire to achieve effective suppression.

4.3. Ensuring fire service equipment meets the standard fire main design

The methodology provided in 7974 to calculate the required firefighting water provision for wet fire mains may also be used for buildings below 50 m in height where dry rising mains are provided, although no such flow requirements are prescribed.

The 50 m height limit is based upon 51 mm attack hose and a fire-fighting branch meeting the minimum hydraulic characteristics of K-value = 230 [23], *(note: the design specification for a BS 5306 dry rising main was calculable to a 235 K-value at 60 m maximum height using 70 m attack hose and a 19 mm smooth-bore branch flowing 100 gall/min (455 L/min)).*

$$K = Q/\sqrt{P} \quad (6)$$

where

K; K-value
Q; Flow (litres/min)
P; Pressure at the branch (bar)

Flow (litres/min) is calculated by multiplying $\sqrt{p}$ by the K value (K).

It is the responsibility of the fire service to meet the 230 K-value required for high-rise fire mains that conforms to the design specifications (since 2006). However, it could be argued that a firefighting branch/nozzle K-value of between 300 and 400 is more appropriate where wet rising fire mains are designed according to BS9990:2015, requiring two 750 L/min attack hose-lines. Whilst 2–3 attack hose-lines > 500 L/min each are rarely necessary for residential apartments or flats, flows of > 750 L/min may well be required for attack lines on open-plan office floors. It is important for fire engineers and the fire service to design and prepare, according to the level of risk likely to be encountered.

Where buildings are not required to have wet risers there may be a need to install dry rising mains. Whilst there are no flow requirements stipulated in UK codes for dry risers the minimum 100 mm mains are designed to enable a fire service pumper to supply the main with water at a working pressure of 12 bar [22] (10 bar pre 2015). A 12 bar inlet pressure will allow an outlet pressure of at least 6 bar at the highest outlet (50 m) and a practical flow-rate of up to 600 L/min for each firefighting jet in use with a 45 m hose-run (depending on hose-line and nozzle diameter, pumping capacity and hydrant capability). As additional hose-line jets are added the flow-rates at each nozzle will begin to reduce as water flow is shared and pump capacity is limited. In large open floor-plates below 50 m a hydraulic analysis of the fire service ability to meet the flow requirements of a 7974 performance based design should be undertaken. Where this falls short, further enhancements to passive or active fire protection measures should be considered.

4.4. Calculating fire service suppressive capacity

Based on the GCU research of real fires, coupled with theory, the cooling effect of water can therefore be calculated using specific heat capacity and latent heat values as follows:

Assume that when one litre of water is applied to a fire, it increases in temperature, turns to water vapour and then the water vapour increases in temperature until it reaches the temperature of the fire gases.

1. To heat water from 10 °C to 100 °C, the energy input required is 90 °C × 0.00418 MJ/kg °C = 0.38 MJ/kg
2. To vaporise water at 100 °C requires 2.26 MJ/kg.
3. To heat the steam further requires an energy input that equals (T–100) × 0.002 [MJ/kg] (specific heat of steam), where T [°C] is the actual steam temperature

This means that to transform 1 kg of water at 10 °C to steam at 600 °C, an energy input of *(0.38+2.26)+(600–100 × 0.002)= 3.6 MJ* is needed. The heat absorption capacity according to Särdqvist [24], is therefore 3.6 MJ per kg of water, used to its maximum at 600 °C.

The rate of heat absorption from the fuel bed required to achieve extinguishment is generally far less than that in the combustion zone, at any given time. It terms of practical fire suppression of room fires, it was noted by Rasbash [25], that the actual efficiency of water absorption in the flaming combustion zone was around 10–20% when considering a combined approach to both fuel-phase and gas-phase suppression. If enough water is applied, the additional cooling effect extracts sufficient heat from the fuel base to take it below its ignition temperature.

Later work (reported in 1979–1984) from several full-scale ventilation controlled fire tests [26], at Karlsruhe University (Fire Research Station) in Germany revealed some commonality during the overall extinguishing process, where 36% of applied water was seen to suppress active (flaming) combustion, with the remaining 64% cooling the fuel base surface fire. This was noted in the live fire tests and then validated using a complex mathematical model developed to support the test process. An undefined amount of applied water may be observed as 'run-off' at building fires and an amount of warm or hot water may remain on the floor or even flow out from the involved fire compartment, having already extracted much of the heat from the fuel base. It is this division in actual firefighting water absorptive capacity that may determine the true practical 'efficiency' (k_w) of application when it comes to the methodologies proposed (Figs. 10–12).

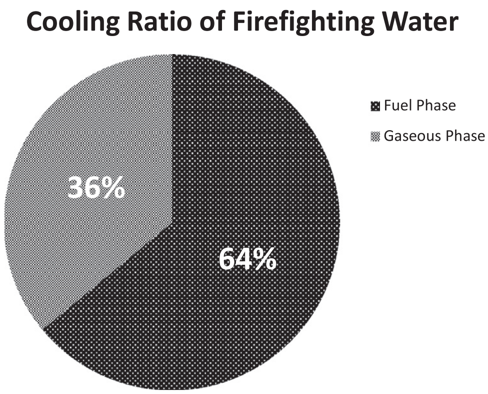

Fig. 10. The cooling ratio of applied firefighting water determined by full-scale ventilation controlled fire tests at Karlsruhe University (Fire Research Station) Tests in Germany 1984.

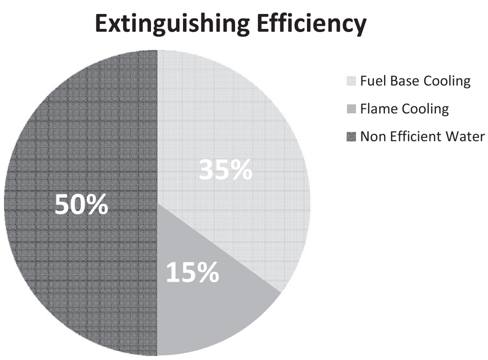

Fig. 11. Research by Rasbash suggested primary efficiency factors of applied firefighting water.

Example one:

19 mm Hp hose-reel tubing × 54 M AT 1.83 l/S (110 l/min)

Flame suppression 0.36% × 3.6 MJ/kg × (1/0.30) × 1.83 L/s × 0.15% = 1.18 MW

Fuel base cooling 0.64% × 2.6 MJ/kg × 1.83 L/s × 0.35% = 1.06 MW

Total; 2.24 MW
Q_s; 2.24/0.5(k_F)
Total heat absorption capacity; 4.48 MW

Example two:

22 mm smooth-bore nozzle at 9.16 l/S (550 l/min)

Flame suppression 0.36% × 3.6 MJ/kg × (1/0.30) × 9.16 L/s × 0.15% = 5.93 MW

Fuel base cooling 0.64% × 2.6 MJ/kg × 9.16 L/s × 0.35% = 5.33 MW

Total; 11.26 MW
Q_s; 11.26/0.5(k_F)
Total heat absorption capacity; 22.5 MW

The maximum firefighting capability of a primary firefighting deployment (hose-line) can therefore be calculated, using Eq. (7) as follows:

$$F = 0.407 * Q_{max} \quad (7)$$

where

F; Required Hose-line Flow-rate (L/s)
Q_{max}; Peak Heat Release Rate (PHRR)

Then by using a time of anticipated firefighting deployment (water applied to the fire), matched against a t^2 fire growth curve, the likelihood of fire control at any point may be estimated providing the fire service have good access to the fire. Therefore if a deployed hose-line has a maximum suppressive capacity of 20 MW (488 L/min), this limit will be reached in just over 21 min on a medium growth curve and in just under 11 min on a fast growth curve. There is additional time to be estimated, being that of the incipient stage of fire growth (Table 7).

The GCU research has also developed National Operational Guidance for firefighters where a simple formula for use on the fire-ground has evolved. In taking the area (A_{fire}) of fire involvement (or the anticipated area in time) in square metres and multiplying by 5 ($A_{fire} \times 5$) the needed flow-rate (L/min) for effective suppression is obtained (area of involvement > 100 m^2). This formula is for use up to 3 m high ceilings and to 500 m^2 of fire involvement. Where ceilings are higher than 3 m, or where industrial/storage buildings are involved, the formula $A_{fire} \times 10$ may be more appropriate, up to 200 m^2 of fire involvement. *(Where exterior wind or higher than average fire loads are encountered the needed flow-rates may be higher than the formulae propose)* (Fig. 13).

Flame Suppression (36%)	0.36 x 3.6 x (1/0.30) x 1 x 0.15	=	0.65 MW
Fuel Base (64%)	0.64 x 2.6 x 1 x 0.35	=	0.58 MW
		Total	**1.23 MW**
Q_s (The heat absorption (MW) of the water used directly on the fire)		=	1.23 / 0.5(k_F)
		=	2.46 MW *per L/s***
		=	1 / 2.46
***Adequate firefighting water** per MW of Q_{max} (PHRR)*		=	**0.407 l/s/MW**

Fig. 12. Based on Figs. 10 and 11, the most effective heat absorption of one litre of water, combined with the observed ratios, of applied firefighting water into the gas-phase and onto the fuel-base, is 0.407 l/s/MW.(Grimwood, Glasgow Caledonian University 2015). **Note:** k_F is the assumed combustion efficiency of the fire (taken as 50%).

Table 7
Minimum needed flow-rates for suppression based on heat release rate (HRR) at 2.46 MW per L/s **

Nozzle	Water flow-rate (l/s)	Water flow-rate (L/min)	Heat absorption capacity (MW)
Smooth-bore 14 mm	4.83	290	11.9
Smooth-bore 22 mm	9.16	550	22.5
Smooth-bore 22 mm	15	900	36.9
Automatic combination nozzle	5.83	350	14.3
Automatic combination nozzle	1.66	100	4.0
Fog nail	1.2	72	2.9
LP Fog Nozzle <1 mm water droplets	5.0	300	12.3
LP Fog Nozzle <1 mm water droplets	7.91	475	19.4
19 mm HP Hose-reel tubing × 54 m	0.75	45	1.84
19 mm HP hose-reel tubing × 54 m	1.83	110	4.5
22 mm HP hose-reel tubing × 54 m	3.3	200	8.1
25 mm HP hose-reel tubing × 54 m	4.16	250	10.2

** Refer to Fig. 12.

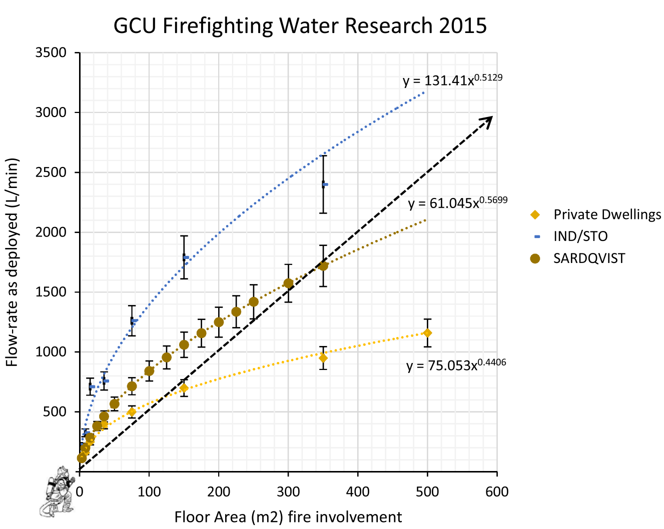

Fig. 13. The GCU research into firefighting water flow-rates used by UK firefighters at 5401 building fires with the A_{fire}x5 fire-ground formula overlaid.

5. Conclusion

The research by Glasgow Caledonian University [27], analysed data from 5401 building fires in the UK from 2009–1012, where active firefighting using water was undertaken by firefighters wearing breathing apparatus. This is the most detailed review of firefighting water usage in the UK to date, that was validated in part through on-board appliance flow metres. It was noted that there is a link between the amount of water deployed during the early stages of a fire and the level of resulting building fire damage. Where early water was deemed inadequate at building fires, this also led to an increase in resource and staffing requirements during the latter stages of firefighting operations.

The results from the GCU research have been used to develop a design methodology for estimating the quantity of water required (as flow-rate or in storage) to effectively extinguish a fire involving large areas in a wide range of occupancies. This method has been incorporated into the publication of BS PD 7974:5:2014 (Fire Service Intervention) and this paper demonstrates' how greater financial savings may be achieved in design, when compared to code compliance. An example of this involves the provision of 150 mm rising fire mains (with at least two outlets per floor) as opposed to 100 mm mains, in large commercial buildings. In some cases less pipework will result with careful configuration of the larger mains, whilst ensuring greater flow density coverage that meets the needs of an the fire service for safe and effective interventions. The data may also be used to quantify the fire suppressive capability of a hose-line or a team of firefighters when deployed to control a developing fire in large open-plan floor space, offering some guidance as to the likelihood of a fire service intervention being successful.

A free calculator tool [28], can be downloaded to enable comparisons of the BSPD 7974:5:2014 s8.5 calculations and solutions explained throughout this paper, using 20–40% sprinkler reductions. When using this tool there are two distinct approaches to 'design calculation' that can be taken:

1. Fire load density
2. Occupancy and floor area (m^2)

The use of 'occupancy and floor area' (2) offers a representation of the flow-rates that were used at the 5400 fires with a mean flow output that ensures critical flow-rates are always exceeded. However, in some circumstances of heavy fire loading (for example High Street book, toy or shoe shops), where the ratio of fire load density to floor area is high (>1200 MJ/m^2), it is perhaps more appropriate to use the 'fire load density' option (1).

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