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The County/Metro research into fire-fighting suppressive capacity and the impact on building fire damage at >5000 UK building fires, 2009–2012

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ABSTRACT

This paper describes research by Glasgow Caledonian University into fire-fighting water flow-rates as actually deployed to control and suppress >5000 building fires that occurred in two fire authority jurisdictions in the UK between 2009 and 2012. One fire service covered a large county suburban risk area with low to medium populated areas, whilst the other covered a large metropolitan region with heavily populated inner city areas included. Using data from the national IRS fire reporting framework (*UK Fire & Rescue Service National Incident Recording System*), it was demonstrated that there are critical links between the amounts of water used/required for effective fire-fighting in relation to the occupancy type, the density of the fire load, the estimated heat release from compartment fires and the extent of fire damage that may impact on the building and its contents.

Comparisons are made to similar research undertaken previously in the UK that estimated water carried to the scene by fire engines (1800 l in the literature) was generally adequate in dealing with building fires on 86% of occasions. Interestingly, some fifty years later, the County/Metro research reported in this paper demonstrates that just 64% of fires are currently dealt with using the 1800 l on-board water provision provided by a single fire response vehicle, although the source of data representation may be different. A deployed flow-rate between 6 and 12 LPM/m^2 per 100 m^2 of fire involvement was generally observed in the current study and the variance was mainly relative to occupancy type.

An existing design methodology for fire-fighting water provisions is then held in comparison to the County/Metro flow-rate data, demonstrating close correlations with this extensive empirical research.

1. Introduction

This research compares the fire-fighting suppressive capacity of a County Fire & Rescue Service (FRS) with that of a Metropolitan FRS over a three year period 2009–2012. The data used have been extracted locally from the national Incident Recording System (IRS), a comprehensive national computerised database used by UK fire services to record all types of emergency incidents, including building fires. The research is specific to internal building fires, not including derelicts, exterior roof or chimney fires. The data have been refined to those fires where an area of internal fire damage was recorded and water was deployed by hose-reel and/or main-line jets/monitors. The data resulted in over 5000 'working' building fires (>4000 Metro and >1000 County). This represents the widest amount of data collated to date in the UK for analysing fire-fighting suppressive capacity. The direct comparison between two UK fire services is also unique.

The large amount of data provided in this research suggests any margin of error is lessened and the final outputs offer a more accurate representation of similar analytical methods used in previous research of such nature. Previous research in the UK has rarely looked at more than 400 building fires. The overriding objective of this research is aimed at optimisation of the service delivery to building fires from a fire service intervention perspective. In order to achieve this, an effective resource allocation of fire cover relies on a minimum fire-fighting water provision along with adequate firefighter access, both to the exterior and within a building, in line with sufficient fire-fighting facilities and fixed fire protection systems to support a safe and extended fire-fighting operation, for what is considered a 'reasonable' time period.

As an example, a fully involved fire load on an upper level open-plan office floor of 1400 m^2 might be expected to progressively burn for around 90 min. During this period firefighters may occupy the space in order to maintain an on-going fire-fighting

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Nomenclature

F_{design}	the design flow-rate for a fully involved compartment burning at maximum intensity (L/s)
F_{growth}	the minimum required flow rate for a growing compartment fire (L/s)
q_k	the fire load density for the enclosure (MJ/m^2)
A_f	total floor area for the fire resisting enclosure (m^2)
A_{fire}	the floor area of fire involvement in m^2
F	required fire-fighting flow-rate (L/s)
k_F	combustion efficiency (0.50)
k_w	cooling efficiency of fire-fighting water (0.50)
Q_w	absorptive capacity of water at 100 °C=2.6/L/s
Q	the total heat release from the fire during the growth phase (kW)
$Q_{\max}$	the maximum heat output of the fire (MW)

operation in an attempt to prevent spread to other floors. An adequate water provision is therefore just as important as the surrounding fire resistance to the structure.

It was reported that in 1992 [1], of 107,437 fires recorded in occupied buildings in the UK, nearly 30% were extinguished without the use of any actual fire-fighting action. A further 12% did not require a hose and 48% were put out with a hose. There were 11,000 fires which required one or more main jets to be used, of which some 1700 (2% of the total) required three or more main jets (a standard pump carries two hose-reel jets and two or four main jets). This report further evaluated fire-fighting task analysis and response to building fires, suggesting that moving away from the existing standard sized fire engines in some circumstances to smaller fast-response vehicles that are equipped and staffed more effectively may optimise intervention to better effect.

This paper describes an evolution on past research into fire-fighting flow-rate requirements for building fires. The previous research, combining the author's data from 100 building fires in London (TFR 1989) with Barnett's SFPE TP/2004-1 methodology [2] was used to estimate needed fire-fighting flow-rates at building fires.

This paper utilises recent research data from the County/Metro study of >5000 UK building fires across a three year period, 2009–2012 to demonstrate comparisons with the earlier research.

Although there was never any prior intention to validate this earlier research, there appears to be good correlation with the current data that suggests the earlier methodology still remains effective as a tool for determining fire-fighting water requirements, fire service intervention and building design, or town centre planning.

This paper supports a methodology whereby minimum fire-fighting water requirements may be calculated according to building purpose groups, fire load, compartment size and fire-fighting intervention procedures. The outcomes can then be checked against actual fire service needs as used in the County/Metro study to ensure greater accuracy in provision.

2. A study of >5000 UK building fires 2009–2012

2.1. The validity of the research

The building fires in this research were considered ‘working fires’ that had entered a growth curve phase, creating fire damage within a compartment requiring firefighters wearing breathing apparatus to be deployed in order to achieve control and suppression. The study did not include exterior fires, garden sheds, residential garages, exterior roof fires, derelict building or chimney fires.

The data are validated in some part by water smart [3] flow-metre technology that recorded actual flows used at fires where flow-metres had been fitted to fire service pumps. The data resulted in over 5000 ‘working’ building fires (>4000 Metro and >1000 County). This represents the most extensive amount of data collated to date in the UK for analysing fire-fighting suppressive capacity and offers benchmarks associated with levels of fire containment or fire spread that may be used for future optimisation of the tactical response.

The data are distributed for comparison across building ‘purpose groups’, as defined in the Building Regulations [4] of England and Wales. This offers a detailed view of fire damage and fire-fighting water usage in a wide range of buildings and occupancies and broadens the research in comparison to previous studies.

At the outset it was necessary to apply flow scales (Litres/minute – LPM) per fire service hose-reel (100 LPM); branch jet (350 LPM County – 500 LPM Metro); and monitors (1000 LPM). These flow-rates per equipment were validated by an extensive range of practical flow tests and furthermore by fire ground *water smart* flow-rate technology, where live flow data recorded at building fires were recorded.

2.2. Impact of fire-fighting water flow-rate on building fire damage

The data analyses for both fire service areas needed to be comparable. From the data, the majority of building fires were less than 500 m^2 and water application was less than 6000 LPM. Therefore it was fires within this category that were used for direct comparison.

It was noted that slightly more water was used at building fires in the Metro area and fire containment was more effective than the county area. The water application was more effective in the Metro area consequentially the fire damage was lower than in the County area. However, it should not be concluded that suppressive capacity is solely responsible for this outcome as there are a number of other variables that may be considered, such as varied fire-fighting tactics and equipment, spatial distribution of fire stations, fire cover provisions, social demography and levels of fire-fighting experience.

However, the method in which water was applied at building fires in the two FRS areas could suggest that flow-rate may have had some direct impact on building fire damage. Despite the fact that the county deployed a similar total amount of water to the metro FRS (12 compared to 12.45 LPM/m^2 overall) the county used more main-line jets (one jet per 2.6 fires) compared to the Metro (one jet per 4.3 fires) to apply fire-fighting water. Therefore a logical conclusion may be that the county required more staffing and resources to deploy the same quantity of water into fires, which may have resulted in the water being applied at a later stage of fire development.

2.3. Non-domestic building fires require higher fire-fighting flow-rates

The main data were divided into ‘domestic dwelling’ fires and ‘all other building’ fires. This was relevant in that fires in private dwellings are likely to occur in smaller compartments than ‘all other’ buildings and this reflects in the needed flow-rates deployed. It has been understood for many years that fires in

Table 1
Data comparisons in the County/Metro fire-fighting research 2009–2012.

County fire service	Metro fire service
The 1152 County internal building fires in the selected zone (< 500 m^2 / < 6000 LPM) demonstrated an average flow of **13.8 LPM/m^2** (domestic residential) compared to **11.8 LPM/m^2** in 'all other buildings'. 73% of all fires were handled using just **hose-reel** (92% in dwellings) with 86% handled by tank supply (< 1800 l) and 14% requiring an augmented water supply. A **total average flow-rate** per incident was recorded at 386 LPM. The **average area of fire damage** per incident was recorded as 39 m^2. *Fire damage to buildings is reflected in the IRS system as broad dimensions between two points. In all cases the average was used as no exact information is recorded. As an example, 75 m^2 is always used to describe the IRS area of 51–100 m^2.* **Fire spread data** demonstrated fire confinement as follows: • Compartment of origin – 50.5% • Floor of origin – 14.11% • Spread to multiple floors – 35.2%	The 4249 Metro internal building fires in the selected zone (< 500 m^2 / < 6000 LPM) demonstrated an average flow of **12.2 LPM/m^2** (domestic residential) compared to **12.49 LPM/m^2** in 'all other buildings'. 80% of all fires were handled using just **hose-reel** (94% in dwellings) with 87% handled by tank supply (< 1800 l) and 13% requiring an augmented water supply. A **total average flow-rate** per incident was recorded at 321 LPM. The **average area of fire damage** per incident was recorded as 30 m^2. *Fire damage to buildings is reflected in the IRS system as broad dimensions between two points. In all cases the average was used as no exact information is recorded. As an example, 75 m^2 is always used to describe the IRS area of 51–100 m^2.* **Fire spread data** demonstrated fire confinement as follows: • Compartment of origin – 56.1% • Floor of origin – 19.8% • Spread to multiple floors – 24%
Use of main-line fire streams (Jets) Main-line jets were used at 27% of fires One jet was used per 2.4 fires Monitors were used at 0.45% of incidents, 75% of these were used at 'all other' building fires.	**Use of main-line fire streams (Jets)** Main-line jets were used at 19.5% of fires One jet was used per 4.3 fires Monitors were used at 0.44% of fires but were often used in pairs, mostly at 'all other' building fires.

non-domestic buildings often require greater quantities of water from the outset in order to achieve control. A breakdown of data into 'occupancy type' groups (UK Building Regulations term these as 'purpose groups') is also presented in this paper (Appendix 'A').

Some comparisons noted in the data demonstrate variations between County and Metro fire-fighting suppressive capacity. The data outcomes may offer some useful benchmarks for measuring performance (Tables 1 and 2 and also Fig.4).

3. Fire-fighting suppressive capacity

3.1. Fire-fighting hose-line deployments

In this research the suppressive capacity of any fire service intervention is matched against fire growth, influencing factors such as the fire load density (MJ/m^2) and the peak heat release of the fire as it changes from ventilation to fuel controlled (Q_{max}).

A fire pumping appliance with a crew of 4/5 can be expected to get a single jet (hand-line) into operation internally or possibly an external monitor. This accounts to a suppressive capacity of 350–1000 LPM, depending on the flow capability of their nozzles. As a broad guide, a 600 LPM fire-fighting jet has a maximum suppressive capacity of around 20 MW. This will be seen through the proposed methodology explained within this paper (for example Eq. (4)).

The primary approach to the majority of building fires is based around a hose-reel attack using high-pressure delivery through one or two hose-lines of 19 mm reinforced composite tubing. This equipment delivers an estimated 100 LPM through each line and in the research dealt with 75% of fires without further support from larger hose-lines.

Table 2
Building fires where 19 mm hose-reels were used effectively without the need for larger hose-line support.

	County hose-reel data	Metro hose-reel data
Number of fires	**840 Fires**	**3418 Fires**
Average fire size	7.72 m^2	11.14 m^2
Average flow-rate	14.73 LPM/m^2	12.36 LPM/m^2
Fire confinement and fire spread	**Room of origin – 591 (72.7%)** **Floor of origin – 118 (14.5%)** **Spread to other floors – 114 (14%)**	**Room of origin – 2621 (71.2%)** **Floor of origin – 601 (16.3%)** **Spread to other floors – 460 (12.5%)**

In some cases two or more reels came into use. In these situations the County demonstrated good effect although at fewer fires. At larger fires the Metro fire service demonstrated better outcomes with reduced levels of fire spread and smaller average fire sizes (m^2) using a reduced deployment of jets than the County, to apply the near same flow-rate (see Fig. 1).

- The County fire service's total hose-reel deployment was 118 percent of their total number of working building fires whilst the Metro fire service's total hose-reel deployment was 117 percent of their total number of working building fires.
- The County's total main-line jet deployment was 42 percent of their total number of fires whilst the Metro's total main-line jet deployment was 23 percent of their total number of fires.
- Assuming an average team of two firefighters per internal hose-line (jets/reels), the County's staffing deployment was 160 percent of their total number of fires whilst the Metro staffing deployment was 140 percent of their total number of fires (total number of hose-lines deployed as a percentage of number of fires).

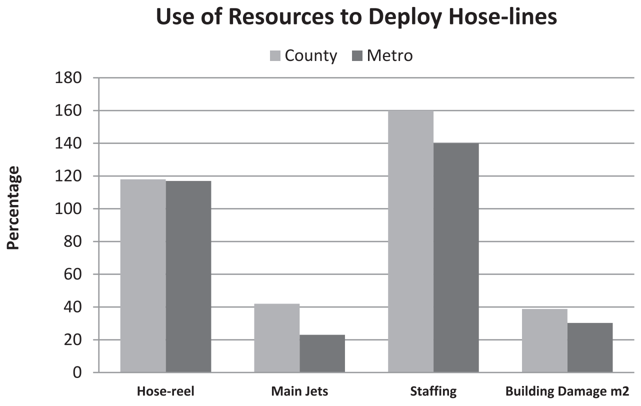

Fig. 1. The equipment and staffing resources used by the County and Metro fire services to deploy hose-lines (*With resulting building fire damage shown in m^2 (averages)*).

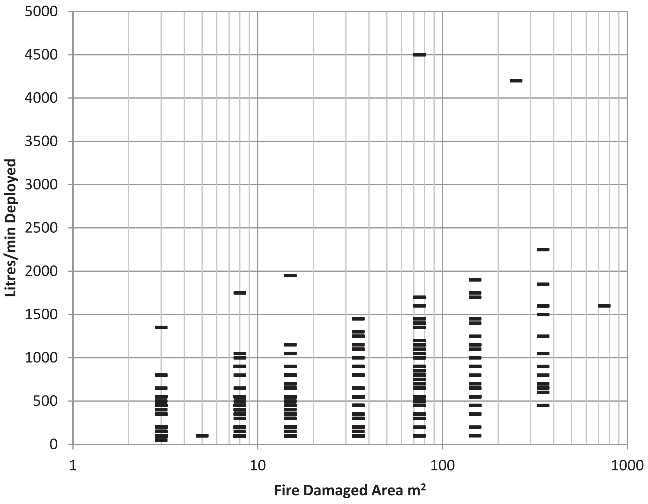

Fig. 2. County 1145 FRS building fires 2009–2012: deployed fire-fighting flow-rates in County within the targeted zone $<500\ m^2$ <6000 LPM where the vast majority of working fires in buildings occurred.

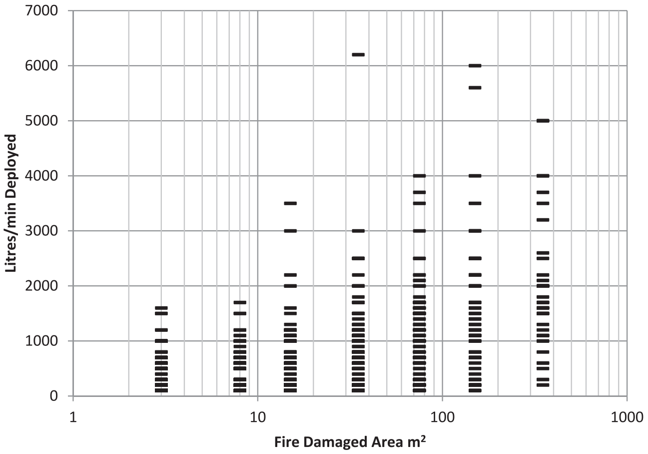

Fig. 3. Metro FRS 4104 building fires 2009–2012: deployed fire-fighting flow-rates in Metro within the targeted zone $<500\ m^2$ <6000 LPM where the vast majority of working fires in buildings occurred.

Table 3
Flow rates in Fig. 5 are graphed according to IRS fire damage data record averages; example $350\ m^2$ covers the broad range of fire damage as recorded in the $201–500\ m^2$ zone.

Area of fire damage (m^2)	Private dwellings LPM	IND/STO buildings LPM
1–5 (as 3 m^2)	130	229
6–10 (as 8 m^2)	160	378
11–20 (as 15 m^2)	250	521
21–50 (as 35 m^2)	400	803
51–100 (as 75 m^2)	500	1184
101–200 (as 150 m^2)	700	1686
201–500 (as 350 m^2)	950	2598

- The resulting average fire size (m^2) for comparison to hose-line and staffing deployments were 39 m^2 (County) and 30 m^2 (Metro).
- In general, the highest flow-rates were used at fires in the Industrial/Storage purpose groups where an average 595 l/min (County) and 572 l/min (Metro) was deployed. This resulted in average fire sizes of 78.0 m^2 (County) and 59.1 m^2 (Metro) in the Industrial/Storage purpose groups.
- Both fire services delivered the same total overall of water per m^2 of fire involvement (12 l/m^2 by County compared to 12.45 l/m^2 by Metro).
- It is suggested therefore that main jets were deployed at later stages during firefighting by County and as each jet flowed less (l/min), in comparison to Metro, the County needed to deploy more jets to deliver what was, in the end, an equivalent total flow rate per area of fire involvement.
- As a way of addressing the early stage fire flow demand, the County fire service involved have since begun a transition towards 22 mm hose-reels as a replacement for the traditional 19 mm reels, as a means of deploying more water onto a fire in its early stages whilst optimising the staffing commitment. The increase in water flow-rate (l/min) between 54 m of 19 mm and 22 mm hose-reel is around 90 percent.

In the County data an average practical limit of 350 LPM compared to 500 LPM in the Metro area for main branch hand-lines has been applied to the methodology used to record and measure data. These estimates are based on either extensive practical flow tests and/or are further validated by water smart flow metered technology demonstrating actual fire-ground flows (Figs. 2 and 3).

Fig. 5 and Table 3 demonstrate average fire-fighting flow-rates as deployed into >5000 UK building fires 2009–2012. This indicates that private dwelling fires, despite having high fire loads attributed, generally require less amounts of water than other building fires. The purpose groups of storage and industrial (IND/STO) required the highest fire-fighting flow-rates with shops, offices and assembly buildings falling mid-range between the two lines. Residential building fires were located lower to mid-range in terms of required flow rates.

There were some differences between the County and Metro tactical approaches and fire cover provisions that resulted in some variance in applied water flow-rates (Fig. 6). In comparison to the metropolitan fire service, generally the county fire service relied on higher deployed flow-rates for smaller buildings but was unable to match the needed flow-rates for more severe fires in larger buildings. The consequential impact this had on the levels of fire damage to buildings is discussed later.

3.2. *Fire-fighting flow-rates – key points including large fires $>500\ m^2$*

The key points are that in the analysed zone ($<500\ m^2$ <6000 LPM) which is representative of the vast majority of fires attended by the fire service, maximum flows generally exist between 1000 and 2000 LPM.

Large fires $>500–10{,}000\ m^2$ were also researched through the County/Metro project and it was generally noted that beyond 600 m^2 of floor space fire involvement the fire service are generally restricted in their capacity to transport sufficient amounts of water to the fire scene whilst a fire remains on the growth side, or at steady state peak, of a fire development curve.

When open floor space $>600\ m^2$ becomes involved in fire it normally requires a greater depletion of the fuel load, into the decay stage, before the available flow-rate can begin to have any positive effect in suppression. The suppressive capacity of a fire attack generally begins to lose effectiveness as the applied flow-rate falls below 3.75 LPM/m^2 [5]. The *critical flow-rate* below which fire-fighting hose-lines can generally be expected to fail in suppression is seen below an applied rate of 2 LPM/m^2.

The flows as deployed at 70 large fires in the study conform closely to current guidance provided by the LGA/Water UK document [6]. Taking industrial buildings as an example it is seen in Appendix 'A' that the actual deployments of firefighting water for industrial building fires in both the County and Metro areas together was 0.16 LPM/m^2 compared to the 0.12 LPM/m^2 water provision recommended by Water UK (Fig. 7).

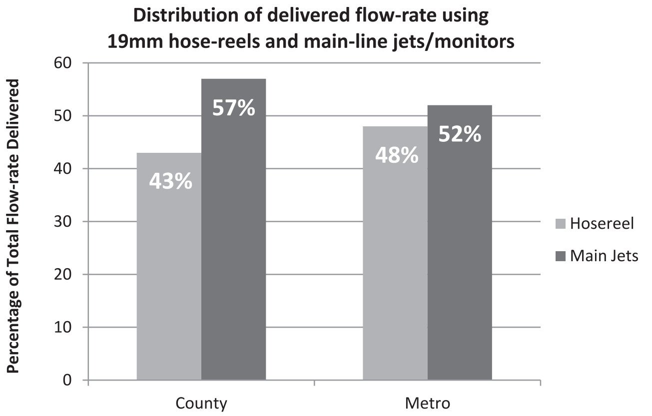

Fig. 4. The distribution of delivered flow-rate at 5401 building fires 2009–2012, between first-aid hose-reels and main-line jets.

4. Fire spread and areas of fire damage

4.1. Compartment fire sizes

The energy release rate from a compartment or room fire is dictated mainly by the energy in the fire load, the surface distribution, the geometric configuration of the room and the amount of ventilation available to the fire. The size of compartments associated with building occupancy types will also have major impact on the extent of fire development and the required firefighting water flow-rate.

In building design, various property groups are designated into categories for the purpose of simplifying the design process. In large complex buildings the fire load and anticipated energy release may be calculated individually.

Also attributed are various fire growth factors that may be used to estimate the speed of growth that could be expected once a fire advances onto a fire development curve.

In County, an average compartment or room fire calculated from the data was 17 m^2 (dwellings) and 38 m^2 (all buildings). Taking a 7% ventilation factor as an example, these fires are likely to result in an energy release of **3–8.5 MW**.

In Metro an average compartment or room fire was calculated from the data as being 16 m^2 (dwellings) and 30 m^2 (all other buildings). Taking a 7% ventilation factor as an example, these fires are likely to result in an energy release of **3–7.5 MW**.

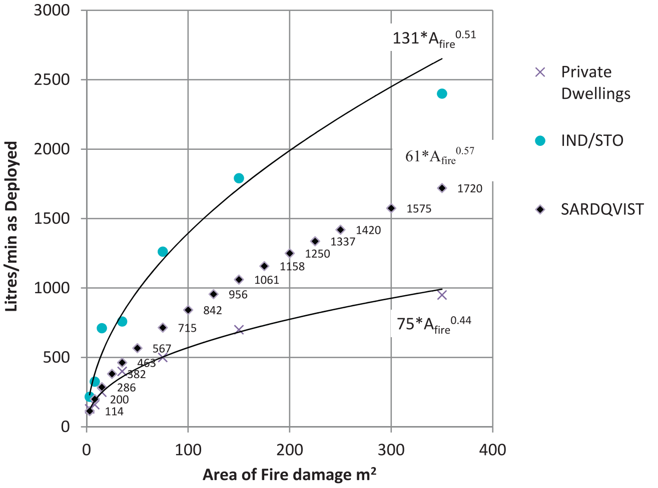

Fig. 5. UK building fire-flow data 2009–2012 (County/Metro research project) A comparison of flow-rate deployments for private dwelling fires (lower trend line); and Industrial/Storage (upper trend line) with the broad range of ‘all other building’ fires falling within the two trend lines (represented by the work of Sardqvist [11]).

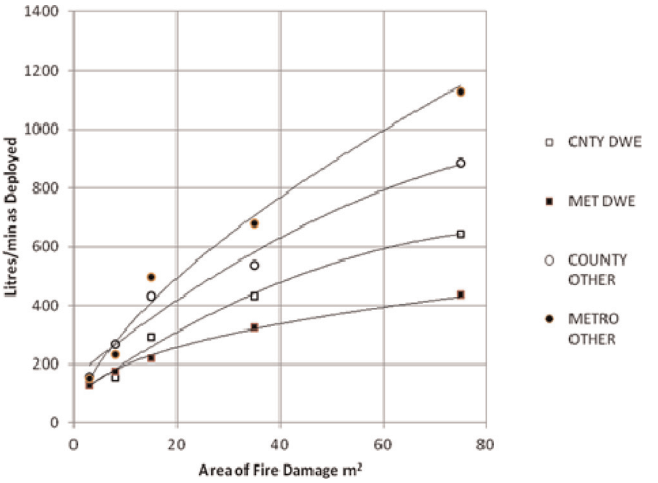

Fig. 6. County/Metro building fire fire-flow research >5000 working fires 2009–2012: building fire flow-rate deployments for County/Metro in Dwellings and ‘All Other’ building types.

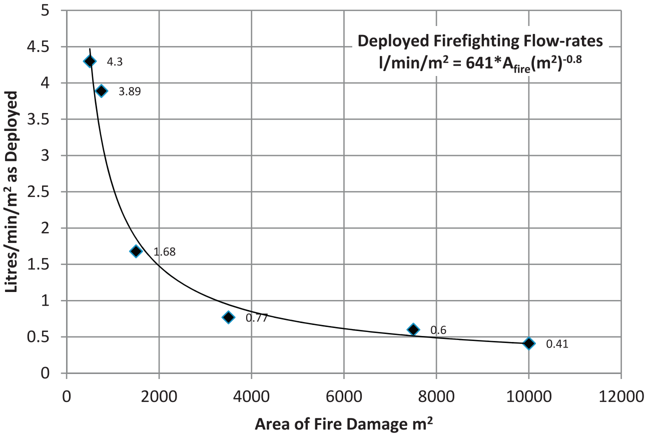

Fig. 7. County/Metro building fire fire-flow research >5000 working fires 2009–2012: deployed flow-rates at large fires involving >500 m^2 of floor space.

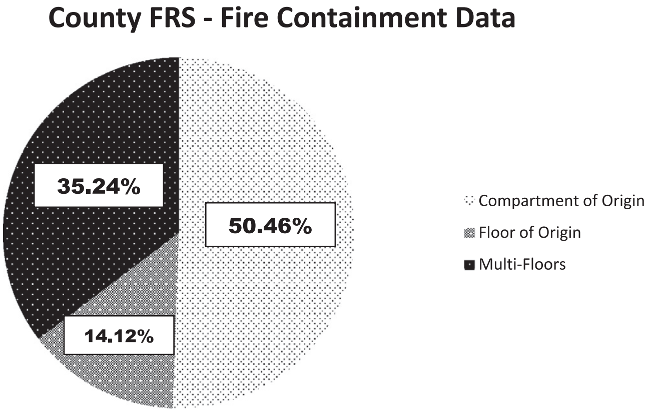

Fig. 8. Levels of fire spread or fire containment in the County Area.

Just as it is possible to measure needed or deployed flow-rate against floor area (m^2) it is equally viable to measure against a fire's anticipated energy release and this is the basis of much research of a similar nature [2].

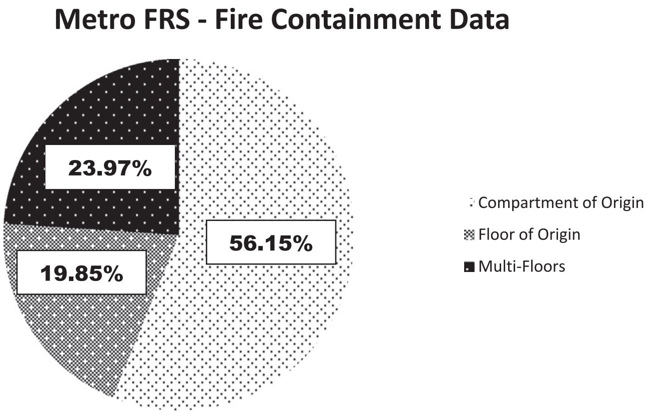

Fig. 9. Levels of fire spread or fire containment in the Metro Area.

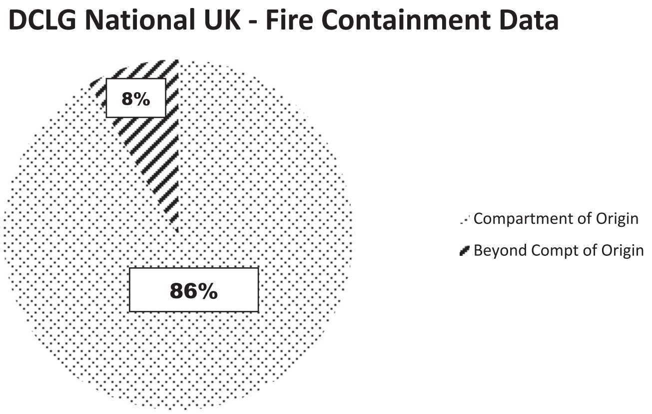

Fig. 10. Nationally recorded (DCLG) levels of fire spread or fire containment for all building fires (many of these were recorded in IRS as 'no action' by brigade).

4.2. *Fire containment and fire spread*

The link to levels of fire containment or fire spread in building fires may be seen in Fig. 1 and also below (Figs. 8 and 9). It can be seen below that the containment of fire spread was generally more effective in the Metro data than the County data. There may be many reasons for this beyond suppressive capacity alone so no direct conclusions should be drawn.

However, for the purposes of this work, it is important to establish a benchmark from which future fire-fighting response and deployment can be measured against and this data may serve good purpose for that reason alone.

5. Calculation methods for estimating fire-fighting water requirements

5.1. *International fire-fighting flow-rate research*

There have been several attempts to generate a range of formulae by which fire-fighting water needs can be estimated, based on a theoretical analysis of water's cooling properties or empirical research of real fire data. In some models both of these approaches have been combined.

These fire-fighting intervention models or building design guides often promote a wide variance in recommended fire-fighting flow-rates needed to control and extinguish fires. In some of the models the methodology may be open to question where source input data is derived from small scale laboratory fires, or where specific fire-fighting techniques limit the use of resulting formulae. In other cases the source data or the methodology may appear incomplete, or is structured without any in-depth validation.

Many of these models base their formulae on a 0.32 water application efficiency factor which supports laboratory or experimental research, suggesting water applied to enclosure fires demonstrates 32% efficiency in suppression [7,8]. Other models utilise empirical fire flow data obtained from a limited number of building fires in a specific demographical or societal setting to develop fire-fighting flow-rate formulae (Fig. 10).

The >5000 fire County/Metro research serves to validate an already existing methodology [2] with supporting formulae, based on previous empirical research of building fires. When selecting a model for the evaluation of required minimum fire-fighting flow-rates for both design purposes and intervention performance indicators, the methodology should be carefully assessed against the primary source data used to develop the model. The most obvious aspects that may change outcomes are water application efficiency factors and the performance of fire-fighting interventions and standards of fire cover, matched against building standards where empirical research is used.

A comparative review of existing models, including FBIM; NFPA 1142; CESARE; ISO (USA); FRAME; FIERA (NRC); LGA/UK Water; NZFS SNZ PAS 4509; IFB/IBC; ISU IOWA; and the NFA (USA) approaches to calculating fire-fighting water requirements, along with more recent work by Hadjisophocleous and Richardson [9] can be made.

6. An engineered approach to estimating fire-fighting water provisions

6.1. *A methodology for calculating needed fire-fighting flow-rates*

This approach to calculating fire-fighting flow-rate, using a validated engineering methodology, is based on a solid foundation of empirical research undertaken by London Fire Brigade Fire Investigators dating from 1989 onwards. The data are then compared to the current research data provided within the UK County/Metro analysis of >5000 building fires occurring between 2009 and 2012.

When addressing fire-fighting water provisions it is essential to design to a reasonable worst case fire scenario and match this to a realistic intervention time-line, taking the suppressive capacity and resource capability of the responding force into account. This is critical if firefighters are to be considered part of the building's fire strategy where they might be expected to occupy fire involved areas to the limits of fire resistance and structural stability.

The maximum quantity of water that is manageable by a 2–3 person crew of firefighters advancing a single internal attack hose-line (fire-fighting hand-line 'jet') is 500–750 LPM. However inappropriate hose and nozzle size/design combinations, as well as the effect of laying hose in confined spaces, may restrict or limit such flows to <250 LPM per firefighting jet, particularly in tall buildings fitted with dry rising fire mains [10].

It is therefore useful for the fire engineer to analyse the suppressive capacity and estimated timed deployment of a fire service's primary and secondary hose-lines, in order to match achievable flow-rate with the fire design's growth curve when producing an intervention timeline. Where 'fast' or 'ultra-fast' fire growth rates are considered possible in large open-plan areas $>250\ \text{m}^2$, but particularly at height within a building, then the fire service might not be able to deploy sufficient flow-rate quickly enough. In this situation reducing the compartment size or providing an automated fire suppression system may be considered.

The following methodology is recommended for calculating the required water provisions needed for fire-fighting in compartments.

Eq. (2) is the outcome of input data used in the SFPE (NZ) model [2]. It is worth noting that efficiency factors in relation to (1) the enclosed fire's combustion efficiency, and (2) applied water cooling efficiency, are key inputs to any model used to estimate fire-fighting water provisions. It is surprising that few other water models have effectively addressed such efficiency factors or in some cases even considered them at all. However, with the adopted approach in this methodology, it will be seen that the above efficiency factors are actually cancelled out by each other, in overall water requirements, for generic fire-fighting scenarios.

The combustion efficiency of a compartment fire has been generally well researched and for a building fire this rarely exceeds 45%, thus an efficiency value of 0.50 can be considered a conservative and upper limiting value for design purposes. This equates to an equivalent gross heat of combustion of 9 MJ/kg if a net heat of combustion of 18 MJ/kg [2] is taken to cover a mix of wood and plastic.

The cooling efficiency of fire-fighting water is also something that has been researched extensively. The efficiency of a fire-fighting stream can never be applied at 100% effectiveness, although for building fires the cooling efficiency of water for fire-fighting ranges from 0.3 to 0.6 [11]. In actual fire-fighting operations at real building fires it has been estimated that water has a generic efficiency level at around 50% (0.50) when used internally to control and extinguish well developed compartment fires. This means that half of the water applied plays little or no part in controlling fire spread.

6.2. Calculating required fire-fighting flow-rate

The combined efficiencies of an enclosed fire's burning rate and that of applied fire-fighting water can be seen in the following equation:

$$F = \frac{k_F Q_{\max}}{k_w Q_w} \qquad (1)$$

where F is the required fire-fighting flow-rate L/s, k_F is the combustion efficiency (conservatively 0.50), k_w is the cooling efficiency of fire-fighting water (conservatively 0.50), Q_w is the absorptive capacity of water at 100°C=2.6/L/s, $Q_{\max}$ is the maximum heat output of the fire (MW).

In simple terms this means that for each MW of $Q_{\max}$ in a fire, the fire fighting water flow will need to be 0.50/(0.50 × 2.6 MJ/kg)=0.385 L/s/MW of $Q_{\max}$ where 1 kg of water at an initial temperature of 18 °C converted to steam at 100 °C will absorb 2.6 MJ of heat energy. Therefore, using fire-fighting water at a conservative 50% efficiency to control a fire burning at a conservative 50% efficiency, the calculated flow-rate provisions for any particular scenario should be considered a minimum flow-rate.

As a design tool Barnett developed a method to calculate the design fire-fighting flow-rate for specific occupancy floor space, based on the inputs from TFR 1989 into TP2004/1 [5]:

$$F_{\text{design}} = 0.00741\left(q_k A_f\right)^{0.666} \qquad (2)$$

where F_{design} is the design flow-rate for a fully involved compartment burning at maximum intensity (L/s), q_k is the fire load density for the enclosure (MJ/m^2), A_f is the total floor area for the fire resisting enclosure (m^2)

Barnett informs on the source of Eq. (2) (below) in SFPE(NZ) TP/2004-1 as follows:

‘An extensive study of various floor areas, ventilation opening ratios and fire load energy densities (FLED's) was carried out as background research, resulting in over 700 pages of calculations and graphs. The floor areas ranged from 200 to 5000 m². FLED's selected were 400, 800 and 1200 MJ/m². Ventilation openings ranged from 2% to 20% of floor area. Ceiling heights ranged from 2.4 to 6.0 m using the former for small buildings and the latter for large. Growth and decay coefficients were selected as 225 and 900 s/MW respectively. Net heat of combustion was selected as 18 MJ/kg to cover a mix of wood and plastic. It was noted that the fires were ventilation controlled (VC) at the low end of percentage openings but, at some point as the ventilation increased, the fires switched to fuel surface controlled (FC). The fire intensity did not increase from that point onward regardless of any further increase in ventilation openings.

It was noted that the greatest fire intensity Q_{max} occurred at the VC/FC changeover point. This was then taken as the most conservative answer for that particular floor area and the corresponding fire fighting water flow’.

To estimate the required design flow rate (L/s) needed to extinguish a compartment fire of maximum intensity, at the VC/FC crossover point –

Example 1. A 70 m^2 apartment (flat) on the tenth level of a high rise building with 60 min fire resistance to the separating boundary walls.

Fire load density for 80% fractile of dwellings=870 MJ/m^2 (Table A.19 PD 7974-1). If exact fire load density information is available for a specific building, that data should be used in these equations.

$$\begin{aligned} F_{\text{design}} &= 0.00741(870 \times 70)^{0.666} \\ &= 0.00741 \times 60900^{0.666} \\ &= 11.4\ l/s \\ &= 683\ \text{LPM} \end{aligned}$$

Example 2. A 600 m^2 open plan office floor on the seventh level of a high rise building with 60 min fire resistance to the boundary walls.

Fire load density for 80% fractile of offices=570 MJ/m^2 (Table A.19 PD 7974-1:2003)

$$\begin{aligned} F_{\text{design}} &= 0.00741(570 \times 600)^{0.666} \\ &= 0.00741 \times 342000^{0.666} \\ &= 35.9\ l/s \\ &= 2156\ \text{LPM} \end{aligned}$$

It should be noted in these two examples that the fire service often requires an additional amount of water at an incident that is over and above that required to extinguish the fire. Additional water is required for safety (back up) hose lines and for hose-lines

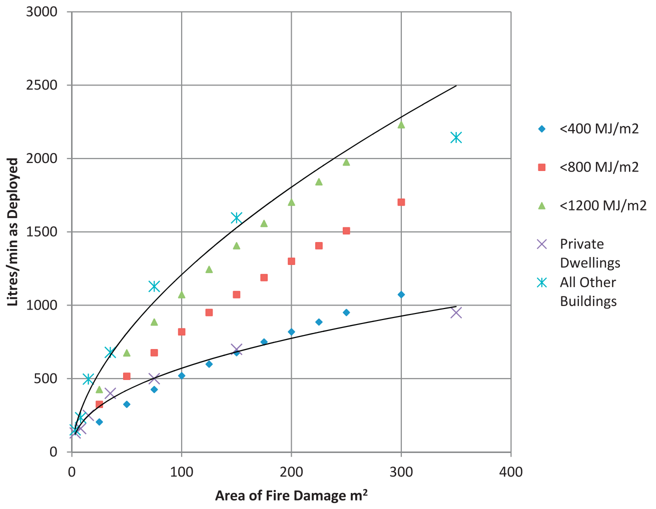

Fig. 11. Close correlations exist between the County/Metro research data lower (dwellings) and upper ((all other fires including IND/STO) boundary trend lines) and the building design flow-rate Eq. (2) proposed by Barnett [2].

used to cool surrounding risks to prevent fire spread and to provide personal protection for firefighters.

Therefore, it is important to acknowledge that the provision of fire-fighting water to a building may exceed the design flow rate calculated for purely fire-fighting operations. In Example 1 a 1500 LPM fire main may suffice whereas in Example 2, at least two 1500 LPM fire mains are needed to provision the 600 m^2 floor plate with an adequate fire-fighting water supply.

It can be seen (Fig. 11) that design flow provisions according to Eq. (2) are closely correlated within the lower and upper boundary flow lines resulting from the 2012 County/Metro research findings. The lower trend line and data points conform to dwelling fires in the research whilst the upper line represents 'all other building' fires along with larger storage and warehouse type fires, according to fire loading and compartment size.

6.3. Fire-fighting ‘task-analysis’ approach (developing fire)

When modelling fire development using a fire-fighting task analysis it may be necessary to consider the effect of the application of fire-fighting water to a growing fire. A growing fire is not fully developed, is most likely ventilation controlled and does not affect the whole compartment. This approach allows an assessment to be made of the capability of the FRS intervention in deploying adequate resources according to a timeline analysis.

Example 3. The fully developed fire described in example two required a water design flow rate of 2156 LPM to control it. How much water would be required to begin to control this fire if fire-fighting began during the growth phase (t=720 s)?

Assuming a fast growth rate common to open-plan office floor-space, calculate the rate of heat release after 720 s (prior to full development):

$$Q = \alpha(t - t_i)^2 = 0.047 \times 720^2 = 24,365 \text{ kW} \tag{3}$$

where Q is the total heat release rate from the fire during the growth phase (kW), t is the time from ignition (s), t_i is the time of ignition (s), α is the fire growth parameter (kJ/s^3)

Required fire-fighting water flow rate for a growing fire:

A simple fire-ground ‘rule of thumb’ approach can be used to assess the fire-fighting task analysis against a growing fire between 50 and 250 m^2 of floor space (fire involvement) as follows:

$$F_{\text{FIRE}} = A_{\text{fire}}6 \tag{4}$$

where F_{FIRE} is the required water flow-rate to deal with a growing fire (LPM), A_{fire} is the floor area of fire involvement in m^2, 6 is 6 LPM/m^2 of fire involvement (for medium fire loads 50–250 m^2 floor area)

Therefore

$$A_{\text{fire}}(Q/Q'') = 24365/200_{*} = 122 \text{ m}^2$$

$$F_{\text{FIRE}} = 122 \times 6 = 732 \text{ LPM}$$

where $Q''$is the is the total heat release rate per unit area of fire (kW/m^2). **Estimated Q'' (kW/m^2) using engineering analysis for a growing fire.*

Therefore, from the moment the fire enters a fast rate of t^2 growth the FRS intervention needs to deploy a minimum flow-rate of 732 LPM within 12 min to be able to suppress such fire spread. A lesser amount may slow the spread of fire but will struggle to effectively extinguish the fire. However, this result must be tempered by considerable engineering judgement and fire-fighting experience and other formulae might be used to calculate Q. Where cellular office space broken down into small (<50 m^2) compartments exists, a medium t^2 growth rate may be assumed.

6.4. Further work by Sardqvist

Work undertaken by Sardqvist [11] involving the analysis of 307 fires that occurred in London between 1994 and 1997 looked at fires in ‘non-residential’ buildings. Although this work is limited to certain building types, the data is again useful in validating the proposed methods to calculated needed flow-rates.

The building types reported in the research were restricted to public and commercial buildings; schools; hospitals; industrial premises; hotels and boarding houses. These occupancy types represent all four categories of fire damage risk being, low; medium; high and very high.

It can be seen in Fig. 5 that Sardqvist's formulae (Eq. (7)) for calculating fire-fighting flow-rate provisions produces a flow-rate curve that falls very much towards the centreline of the County/Metro data lines and within the range of building types referred to in the research. This is to be expected.

This formula can be used on its own to estimate the required fire-fighting water provisions for more general applications and also serves as a simple hand calculation for checking other more complex methods where greater precision in the calculation process is sought.

The trend line formulas (Eqs. (5), (6)) as outputs from the 5401 building fire study by Glasgow Caledonian University, along with work by Sardqvist [11], can also be used to validate the design formula based on fire load produced by Barnett (Eq. (2) and Fig. 11).

For fires in dwellings (house, flats, maisonettes and apartments):

$$F_{\text{dwe}} = 75A_{\text{fire}}^{0.44} \tag{5}$$

For fires in factories, industrial units and storage warehouses:

$$F_{\text{ind}} = 131A_{\text{fire}}^{0.51} \tag{6}$$

For fires in public, office, commercial, schools, hospitals, hotels and smaller industrial buildings (based on the research by Sardqvist):

$$F_{\text{other}} = 61A_{\text{fire}}^{0.57} \tag{7}$$

where F_{dwe} is deployed Flow-rate (LPM) for dwellings, F_{ind} is deployed Flow-rate (LPM) for factories, industrial and storage warehouses, F_{other} is deployed Flow-rate (LPM) for ‘all other’ buildings (Sardqvist), A_{fire} is floor area of fire involvement (m^2).

7. Conclusions

All fire and rescue authorities in the UK are required by law 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. There is no quantitative reference in the acts or in existing prescriptive guidance that accurately defines what an ‘adequate’ provision of firefighting water is, despite calls for guidance from water authorities, although some benchmark guidance [6] based on research undertaken in the 1950s is entrenched in existing codes. It is further noted that adequate fire-fighting facilities and access to buildings must be provided to enable this water to be effectively deployed.

Through data collation and analysis this research has identified the quantities of water (LPM) being deployed by firefighters to control and suppress a large number of building fires in two UK fire authority jurisdictions over a three year period 2009–2012. The outputs correlate well with earlier research undertaken by the author that included extensive fire scene investigation. Based on this data a quantitative approach was used to establish just what an ‘adequate’ provision of firefighting water might mean.

The process of recording IRS data by the fire service may be open to some variables in accuracy but such a large amount of data has never been undertaken before, for evaluating firefighting water requirements against building fire damage. This large number of building fires serves to reduce any percentage of error that might be considered. The data correlates well with existing methods of calculating firefighting water as demonstrated.

A *critical* flow-rate is identified below which effective fire suppression becomes problematic and *minimum* and *optimum* flow-rates are further identified as ‘target’ flows for effective building design and fire service deployments. It was observed that firefighting water demands were commonly dependent on the dimensions of fire involved compartments as well as assumed occupancy fire loads. A secondary analysis was also made of the impact of ‘inadequate’ water on the levels of building fire damage caused although conclusions were never intended to be complete and further research in this area may be justified.

A range of existing design methodologies used to estimate the amount of water that may be needed by firefighters to achieve successful fire suppressions were explored and compared to the 5400 fire study and two existing methods correlated reasonably well. This information is useful to building design engineers, regulators and will also be useful to the fire service when realising their limitations in fire suppressive capacity. It is suggested that this approach also determines specific points on a time-line where a firefighting intervention may begin to fail and active and/or passive protection might require additional enhancement.

The outcomes of the research suggest that current UK regulatory guidance and standards do not give an accurate reflection of the quantity of water required to deal with growing fires in large commercial or high-rise office buildings, particularly where automated fixed fire suppression is non-existent. Therefore in future design, it is recommended that 100mm rising fire mains should be increased to at least 150 mm with two outlets per floor, protected by firefighting shafts, stairs and lobbies. The spacing of such fire mains should account for existing maximum hose-lay distances as well as adequate firefighting water requirements for a single fully involved fire floor at the very least. Singapore fire codes CP29:1998 and SS575:2012 could be referred to as ideal models.

The outcome of this author's research is forming a substantial part of the revision to British Standard PD 7974 part 5, (Application of Fire Safety Engineering Principles to the Design of Buildings) due for publication in 2014. This guidance document is intended to provide an understanding of both the capabilities and limitations of fire service intervention, and takes into account the physiological demands on fire-fighters, the fire-fighting procedures that are used and the limitations of fire-fighting equipment. The methodology proposed throughout this research is aimed at improving the efficiency and effectiveness of fire and rescue service intervention, as well as determining the limitations of any particular intervention strategy as a design feature. It can then be determined subject to fire service involvement at the Qualitative Design Review (QDR) stage of the design process, at what point on a timeline of a fire development curve, further enhancements in building fire protection may become necessary.

In designing a building’s ability to contain fire spread and prevent smoke movement into occupied areas and protected escape routes, so that occupants are able to evacuate to (or remain in) ‘safe’ zones, it is imperative that compartments are limited in size or effective suppression systems are in place to control fire spread. In tall or complex occupied buildings it is even more important that occupants who are unable to simultaneously evacuate are effectively protected and ‘defended’ in place. Whilst it has commonly been proposed that complete compartment ‘burn-out’ without fire service intervention may be used as a design concept, current analytical and computational tools are unable to provide a realistic definition of the effects of a fire on the structural frame and an adequate quantitative assessment is therefore not considered viable for tall buildings at this point in time [12]. Any Fire Strategy for ‘phased evacuation’ or ‘defend in place’ buildings should therefore establish an integrated design solution that includes fire service intervention with sufficient active or passive fire protection measures in place.

Furthermore, a primary functional design requirement of building regulations is that a building shall be designed and constructed so that, in the event of fire, its stability will be maintained for a ‘reasonable period’. This time period must be sufficient to allow occupants to evacuate safely, or remain in place whilst firefighters extinguish the fire. In large, tall or complex buildings there may be an expectation that the fire service is able to extinguish the fire prior to structural collapse. It is shown by case history that large fires in such buildings may come close to compromising structural safety before firefighters are able to extinguish the fire and adequate firefighting water provisions and/or active/passive protection may be critical. This area of the study suggests more research is necessary from a fire engineered structural design perspective and also that adequate water storage provisions, fire service connections and fixed pumping arrangements in such buildings be further researched.

Whilst every effort is taken to ensure flow-rate data was accurately determined in this research, the use of water-smart flow-rate technology is increasing and flow-metres are becoming more commonplace on fire engines. However, it is said that developing a firefighting water model based on flow-rate alone may not be as accurate as using ‘total water applied over time’. Nevertheless, in using ‘total flow applied’, this never guarantees that an average flow over time may accurately represent the variance between ‘critical’, ‘minimum’ and ‘optimum’ flow-rates. Even when analysing current flow data using on-scene flow metres, this research observed how dynamic the constant opening and closing of branch nozzles may be at fires and in each case, the maximum flow-rate recorded was taken as the ‘optimum’ rate of flow as it was assumed this was being delivered at the point in time when the heat release was at its greatest.

Although there are several mechanisms involved in the extinguishment of confined post flashover fires, it was generally concluded by other researchers [13,14] that cooling the fuel base (primary) and flaming gas-phase (secondary) were clearly the dominant factors of extinction, although the use of indirect fog tactics or the introduction of finely divided water droplets into non or lowly-ventilated areas would greatly enhance the mechanism associated with the production of water vapour and oxygen displacement/dilution.

In future years, the retrieval of flow data will become more accurate and the deployment and actual use of firefighting water will be more easily determined. It is suggested that future research in this field takes into account such innovations. Also, the potential for water additives, including foams and compressed air foam (CAFS) enhancing the suppressive capacity of firefighting water in large, tall or complex buildings is likely to drive future research in relation to active fire protection systems and adequate firefighting water storage requirements.

Appendix A

County	Group	Incidents	m^2	LPM	LPM/m^2	LPM/ incident	Average fire size m^2	Room %	Floor %	Multi-floor %	H/ reels %	Tank %	AUG %
	Dwellings	839	14113	195360	13.84	232.84	16.82	61.74	16.69	21.57	92.37	–	–
	RESI INST	24	881	7350	8.34	306.25	36.7	70.83	8.33	20.83	84.5	–	–
	RESI other	43	1260	11250	8.92	261	29.3	39.53	18.6	41.86	81.4	–	–
	Assembly	72	2404	28700	11.93	398.61	33.38	49.32	16.44	32.88	82.33	–	–
County	**Group**	**Incidents**	**m^2**	**LPM**	**LPM/m^2**	**LPM/ incident**	**Average fire size m^2**	**Room %**	**Floor %**	**Multi-floor %**	**H/ reels %**	**Tank %**	**AUG %**
	Offices	23	348	6800	19.54	295.65	15.13	60.87	4.35	34.78	81.96	–	–
	Shops	107	2447	42950	17.55	401.4	22.86	56.07	17.76	26.17	77.31	–	–
	Industrial	35	2194	21050	9.59	601.42	62.68	54.29	8.57	37.14	50.29	–	–
	Storage	9	841	5300	6.3	588.8	93.44	11.1	22.2	66.67	33	–	–
	Totals	**1152**	**24488**	**318760**	**12.00**	**385.74**	**38.78**	**50.46**	**14.11**	**35.23**	**72.89**	**86.35**	**13.16**

Metro	Group	Incidents	m^2	LPM	LPM/m^2	LPM/ incident	Fire size m^2	Room %	Floor %	Multi-floor %	H/ reels %	Tank %	AUG %
	Dwellings	2939	46205	562910	12.18	191.53	15.72	67.68	15.75	16.57	93.81	–	–
	RESI INST	27	187	3500	18.71	129.62	6.92	74.07	18.52	7.41	92.88	–	–
	RESI other	72	907	17000	18.74	236.1	12.59	54.17	11.11	34.72	87.83	–	–
	Assembly	300	5773	70600	12.22	235.33	19.24	64.67	17.33	18	89.67	–	–
	Offices	66	2625	20900	7.96	316.66	39.77	54.55	10.61	34.85	89.79	–	–
	Shops	459	13849	145200	10.48	316.33	30.17	44.66	27.45	27.67	84.39	–	–
	Industrial	288	14690	141200	9.61	490.27	51	46.53	26.39	27.08	59.39	–	–
	Storage	98	6593	64100	9.72	654	67.27	42.86	31.63	25.51	45.9	–	–
	Totals	**4249**	**90829**	**1025410**	**12.45**	**321.23**	**30.33**	**56.14**	**19.84**	**23.97**	**80.45**	**87.05**	**12.95**

Note: Hose-reel data displayed separately – overall 64% of **total fires** were dealt with using tank water without augmenting the supply (86% of **hose-reel fires** used tank water only).

Key: Group – Purpose Groups according to the UK building regulations. **m^2** – area of fire damaged floor space in square metres. **LPM** – Litres/minute flow-rate as deployed to achieve control/suppression. **Room** – percentage of 'working' building fires confined to room of origin. **Floor** – percentage of 'working' building fires confined to floor of origin. **Multi-floor** – percentage of 'working' building fires spread beyond floor of origin. **H/reels** – percentage of fires dealt with using 60 m × 19 mm rubber tubing first-strike fire-fighting hose @ 100 LPM. **Tank** – percentage of fires suppressed using just the 1800 l water carried on fire engine to scene of fire. **AUG** – percentage of fires requiring additional water beyond that carried to scene, augmented from hydrants or other source.

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