Chapter 12

Adequate 'Firefighting Water' – *you need this!*

'As you increase the quantity of firefighting water applied during the first ten minutes on-scene, the data demonstrates the area of subsequent fire damage to the building is reduced and the heat exposure to firefighters is diminished.'

Paul Grimwood (PhD) – 5,401 building fires

If you took a large stack of wood pallets and burned them in the open air, the fire would continue to burn freely in what is termed, a *fuel-controlled fire*. That is, the continuing development of the fire is dependent on the availability of adequate fuel. As long as the distribution of fuel is effective in the stack, the natural airflow would enable most of the fuel to be consumed by the unrestricted fire. However, if we placed a very large fire resisting box over the pallets, with a small opening, the fire would then become dependent on the amount of air supply it received, according to the size of the opening. The fire is now said to be *ventilation-controlled*. With a small opening the fire will not burn well at all and produce much light-coloured smoke, but with a larger opening the fire will begin to burn more efficiently and produce darker smoke. The rate of heat energy being released from the burning pallets is therefore dependent on the size of the openings (*the existing ventilation profile*).

If a single pallet provided heat energy equal to 300 MJ, that equates to 3,000 MJ per stack of ten pallets high. Such a stack would weigh around 160 kg. The British Standards guidance in BS PD 7974 suggests that the average fuel load in dwellings is 780 MJ/m^2. Therefore, a typical room of 16 m^2 in area would require 12,480 MJ of energy provided in pallets to equal the normal average fire load found in residential dwellings. To meet such levels of fire load we would need to provide at least four pallet stacks of ten high in such a room and set light to all of them to reach expected levels of post-flashover heat release. Such a fire would be dependent on the size and number of openings to that room in order to burn efficiently and would burn in a *ventilation controlled* state.

- ***A fire with large openings will burn with greater intensity (higher MW) and will burn down to decay more quickly than a fire in a room with small openings.***
- ***A fire with a higher fire load (say 50 pallets) will still only burn to the same intensity for the same opening size but will burn for longer, as it releases its energy at the same rate and is totally dependent on the amount of ventilation available.***

Figure 12.1: Burning pallets in the open – a fuel-controlled fire Photo courtesy of Terry Johnson

As the burning pallets released their energy much of this (around 30%) would be absorbed into the walls and ceiling surfaces (depending on the thermal inertia of such linings) and would issue from openings as smoke and heat, or even flaming combustion. Some of this released energy would also be stored in the fire gas layers (smoke) that remain within the fire compartment or adjacent areas.

- ***The size, quantity and location of the openings will determine the rate at which the heat energy is released from the fuel load (Heat release rate (HRR) in kW or MW), this is the measure of fire intensity.***
- ***As more windows fail or other openings are created, more heat energy is released from the fire.***
- ***As more energy is released, temperatures near the fire and near ventilation points are most likely to increase.***
- ***As more heat energy is released, more firefighting water is needed.***
- ***As a fire enters its decay stages (fuel depletion), less heat energy is released and therefore less firefighting water will be needed.***
- ***Therefore, we can sometimes control ventilation to a fire (door control) to reduce the heat release, bringing the HRR within reach of the quantity of water we have at the nozzle.***
- ***However, it's always better to have an adequate quantity of water at the nozzle in case of 'unplanned ventilation' caused by the fire!***

As an experiment, you could try to extinguish those forty pallets burning in the open air to see the effectiveness of any particular firefighting stream. Start with a garden hose and then progress through larger fire streams, recording the time taken to extinguish the fire, if at all possible. Typically, a 100 L/min hose-reel will take longer than a 500 L/min solid stream. You may note that the lesser quantity of water you use, the longer it takes to extinguish the fire. In turn, the more time firefighters would be exposed to high levels of heat flux if the same fire is approached in a ventilated enclosure, where the open-air fire plume is turned into a ceiling jet, visibility is restricted by thick smoke, heat is building up and accessing the same fire becomes far more difficult. Therefore, the most effective measure of fire intensity (HRR) is directly proportional to the quantity of water needed to extinguish a room, compartment or building fire.

The amount of firefighting water required is calculated on the ***chemical heat release*** from the fire's fuel load, before it is lost through openings or at boundary surfaces. However, at building fires we can only ever estimate within reasonable parameters of accuracy according to existing experimental data, both the heat release rate (MW) and the needed flow-rate (L/min). A more accurate method may be to record the actual amount used by firefighters at a broad range of occupancy types and relate this to subsequent floor area of fire involvement/damage. This then offers some data that can be used in engineering terms, or for pre-planning firefighting interventions. In such cases it is more important to over-estimate needed flow than under-estimate.

12.1 THERE WERE 5,401 BUILDING FIRES – RESULTING IN GUIDANCE IN BS PD 7974-5-2014

Now there is one of the best known tactical sayings in the fire service. 'Big-fire = Big water'! But when you think of it, a big fire can sometimes be handled by a small amount of water. It all depends on the quantity of fire load involved, the level of ventilation potentially available, or the level of fire containment, the skill of the nozzle operator and the *method* and effectiveness of the *nozzle* used to apply water or foam.

Some key points of guidance – *The **amount of water** (L/min) you have coming out of the nozzle, and your ability to **reach or access** the fire and effectively **penetrate** the involved fire load with **an adequate percentage** of that water, is what will get this job done – have no doubt!*

But how do we determine what 'big water' is and when to apply it? If fire is issuing from one window do you need 'big water'? Let's say fire is issuing from three windows? What if it's going through the roof? How much water is required? We all have different ideas in our mind of the answers! Do you have the staffing and resources to deliver that large amount immediately on-scene? Does the type of construction or the type of occupancy affect the needed amount of firefighting water? As an on-scene **fire commander** how do you quantify how much water you need *now* … and are likely to need over the *next 90 minutes*? How many fire appliances are needed to deliver that quantity of water? If the fire spreads to involve 50 percent of the building in front of you – how do you determine and plan for the required amount of water flow-rate on-scene? If you are a **fire engineer** do you design to prescriptive codes when determining firefighting water requirements from a rising fire main or a building that is five miles from a water source, or do you determine needed flow density on a quantitative basis depending on fire load, occupancy and compartment size? In other words, should a rising fire main provide the same flow-rate density (L/min) in an apartment building as opposed to an open-plan office tower? You might save the client a great deal of money by quantifying needed flow-rate density, matched to the level of risk. A good fire engineer will not only analyse the required flow for the building but also flow-test the available water resources (hydrants) at different times of the day to gain a mean average, before presenting a fire engineered strategy.

There are various means of obtaining an adequate water supply as follows:

1. Water carried on-board the fire engine (generally around 1,500 – 1,800 litres
2. Augmented supply from street hydrants (generally 300 – 3000 L/min ea.)
3. Augmented supply from open water sources, ponds, lakes and rivers
4. Transport of firefighting water via bulk water carriers
5. Water relays (open or closed) set-up between fire engines

On arrival at a building fire, firefighters require immediate access to all parts of the building to allow for a rapid deployment of water onto the fire. In the UK, it has been the 55-metre length of high-pressure hose-reel (or sometimes two) that is used at the vast majority of building fires (76% of working fires). It is for this reason that building regulations require access to all parts of a residential structure (in particular) to be within 45 metres of the fire engine, or a rising main (or sprinklers) may compensate where this is not viable. If the distance to the furthest point is beyond 50 metres as hose-reel is laid into the building, then firefighters are forced to lay larger hose-lines. Extending the hose-reel will dramatically reduce flow-rate and should not normally be done. This will delay the deployment by several minutes and allow the fire to grow and develop further with internal search and rescue attempts also being compromised. Most fires of this nature are dealt with quickly within ten minutes. However, a further 24% of working fires may need additional firefighters to assist as larger hose-lines become necessary. Long hose-lays into buildings beyond 60 metres should be discouraged due to the physiological barriers of firefighters carrying heavy equipment and working in heat for long durations, therefore an adequate number of access points along a large percentage of the perimeter will assist firefighters by reducing needed hose-lay distances and provide less distance to an escape point from the building in emergencies.

To be able to contain a compartment/structural fire safely and effectively, firefighters must ideally be supplied with an *adequate* amount of firefighting water if they are to control a developing fire during the initial stages. This 'early' water 'at the nozzle' must take account of fire in both the gaseous and fuel phases of combustion and to direct water into the overhead gas-phase alone is not always the best way to deal with a fire. It is certainly recommended that every attempt is made to cool hot fire gases using short controlled bursts of water droplets, but it is equally important to try and extinguish the base fire as soon as possible. Research into the optimum use of firefighting streams reported by the author from earlier work showed that when London firefighters used general fog patterns to cool gases and extinguish fire in the gas-phase, and then reverted to straight streams to deal with fire at the fuel base, the measured cooling ratios of both applications combined were 36% gas-phase and 64% fuel-base fire during several experimental full-scale compartment fires.

The Glasgow Caledonian University (GCU) research (author's PhD), analysed Incident Recording System (IRS) data and real time water-smart flow metered data, collated directly from the two fire-grounds of a **county**, and a city **metro**, fire service across 5,401 serious (working) building fires in the UK occurring over a three-year period 2009–2012. This highly concentrated study determined that building fires rarely reached or exceeded a maximum of 500m^2 fire damaged floor area, where the average fire sizes of >5,000 'working' building fires[129] ranged between 16m² of floor area for residential dwellings up to 95m² for industrial units, with all other building and occupancy types falling somewhere in between. For these fires, average firefighting water flow-rate densities ranging between 8 and 12 L/min/m² of fire involvement were used to achieve control. It was noted that once fires had burned beyond 500m² of floor space, the buildings were generally lost completely. Building fires in this research were also broadly seen to spread further than annual government statistical reports would suggest as these were all 'working' fires' and not simply 'calls' to fires. However, 66% of all working building fires in the GCU research were extinguished using just the 1800 litres carried on-board. Based on this study, it is clear that the term 'adequate' firefighting water flow-rate should, in general, be matched against fire load density and compartment size to fire-resisting boundaries.

It has been observed that the accumulation and ignition of hot fire gases in an average UK five-roomed 70m² apartment can cause fire to spread from one room to five rooms in less than sixty seconds. It is also known that steady state fire spread in large open-plan office areas can travel at a rate of 22 m²/min (fast t-squared growth), whilst cellular offices are seen to reduce such fire spread rates to around 7–15 m²/min (medium t-squared growth). Similarly, vertical fire loads in storage warehouses or retail superstores can burn beyond the control of water deployed from a single hand-held firefighting hose stream in less than sixty seconds. It is estimated that a 20-25MW fire is probably the maximum fire intensity a single 500 L/min hand-held hose-line can deal with. Where sprinklers are not installed in such situations the fire service are quite often helpless in containing such rapid fire-growth.

A fire commander needs to be able to immediately estimate fire-ground water requirements with some reasonable accuracy using simple rule-of-thumb guides. A fire protection engineer takes more time in calculating with some greater accuracy, the quantity of water that is best suited to any particular structure using prescriptive or performance based design principles. It is worth pointing out that the quantity of firefighting water needed to protect an apartment building is far less than for open-plan offices or industrial risks, yet existing prescriptive design codes and standards do not allow for any variation when installing rising main (standpipes) and storage water in a range of buildings and occupancies. 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 in residential and commercial buildings, 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 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 abnormally 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 sizes (ventilation factors) have increased over the years.

All fire and rescue authorities in the UK are required by law[130] *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 close access to buildings must also be provided to enable firefighting water to be effectively and promptly deployed.

129 A 'working' building fire in the GCU research was defined as one where breathing apparatus was worn and a flow-rate of at least 100 L/min (hose-reel or main-line hose) was used to achieve control.

130 Fire and Rescue Services Act 2004; http://www.legislation.gov.uk/ukpga/2004/21/contents

12.2 HOW MUCH WATER IS 'ADEQUATE' FOR TACKLING BUILDING FIRES?

To provide 'adequate' firefighting water means that there must be enough water available for firefighters to control fire development during the growth and steady state periods of fire development, in order to protect the structural frame and ensure stability within the building's design limit state. In general, international building 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 (stand-pipe) outlets to the furthest point on a floor plate (usually a 45–60 metre maximum distance).

However, the **flow-rate density (L/min/m²)** of applied firefighting water is rarely if ever, something that is considered or prescribed. A performance based approach takes the flow-rate density factor 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. It also accounts for compensatory reductions in flow and storage, where sprinklers or other protection facilities are provided.

The influence of the fire service intervention depends on the time when the fire service arrives at the fire scene, the resources available and the time when ready to start firefighting (applying water). These issues are thus dependent on the relative distance the fire service must travel to an incident, their availability and the allocation of resources at community level. There is another issue that may become important especially in fires where the performance of automatic suppression systems is inadequate or unavailable. It is the ability of the fire service to extinguish the fire. This issue has been quantified in the NFPA Fire Protection Handbook[131] as curves on the ability of different kinds of firefighting units to extinguish a fire of a given size. The units considered are –

- An average person with an extinguisher is likely to be able to extinguish a fire of ~ 2 m² floor area
- A trained in-house fire brigade. is likely to be able to extinguish a fire of size of ~ 5m² floor area
- An average strength fire department [volunteer, part time or lesser equipped] is likely to be able to extinguish a fire of size of ~ 50m² floor area, where provided with adequate firefighting water
- The strongest fire department [full-time professional or well-equipped] is likely to be able to extinguish a fire of size of ~ 100m² floor area, where provided with adequate firefighting water

The recent publication of BS PD 7974:5:2014[132], based on the author's research published through GCU in 2015, goes some way to fulfilling 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). This guidance was recently called for by representative bodies in both the UK[133] and USA[134]. However, whilst there is prescriptive guidance in place detailing the required firefighting water provisions, it

131 Bush, S. E. & McDaniel, D. L. 1997. Systems Approaches to Property Classes; Fire Protection Handbook. 18th Edition. Quincy, MA: National Fire Protection Association. Pp. 9–92.9–109.

132 BS PD 7974:5:2014, Application of fire safety engineering principles to the design of buildings (Fire Service Intervention), British Standards Institution, 2014

133 Fire Hydrants and Firefighting Supplies; UK Water Industry Research Limited 2010

134 Evaluation of Fire Flow Methodologies; Hughes Associates; The Fire Protection Research Foundation; NFPA January 2014

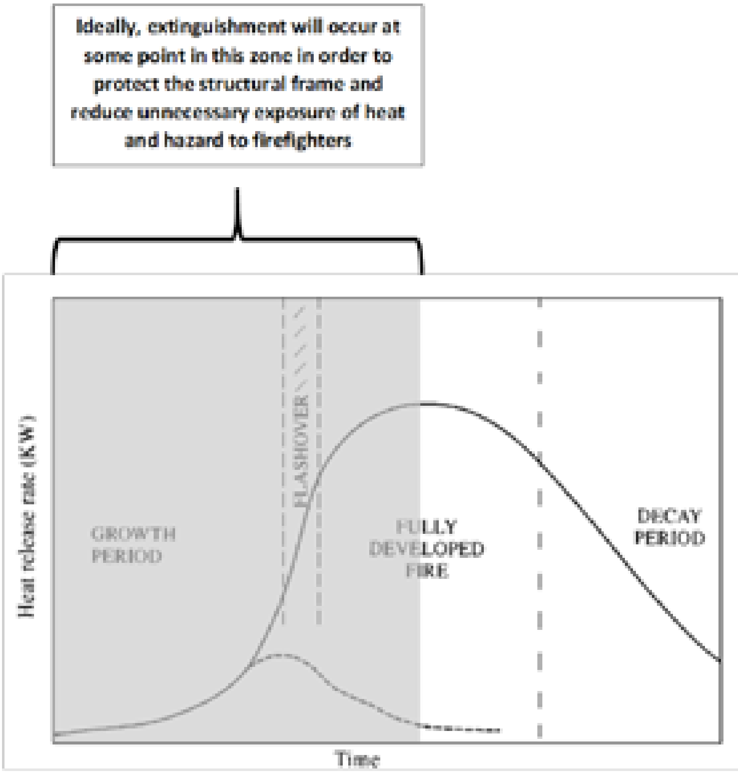


Figure 12.2: The objective must always be to respond, deploy and extinguish the fire within the optimum time frame, to protect the structural frame and reduce unnecessary exposure of heat and hazard to firefighters

is logical that any design engineer or building developer is going to ask why the more onerous recommendations apparent in PD 7974 part 5 should form a part of any fire design strategy. It is important to realise that the base calculations in '7974-5' are for *non-sprinklered* buildings and reductions in firefighting water can be achieved through the addition of a sprinkler compensatory coefficient to the calculations. There are several options open to the fire engineer to include a coefficient in the base calculations as compensation for sprinkler protection, where provided. An objective should be to deliver adequate firefighting water provisions integrated within an active/passive fire protection and management strategy that remains cost effective but is effectively risk based.

Critical firefighting water flow-rates:

In the GCU research used to form the fire engineering design methodology in BS PD 7974:5, the following benchmarks were demonstrated against fast developing fires in non-sprinklered compartments:

• **Critical** flow-rates, below which a developing fire is unlikely to be controlled during the growth or steady state periods.	**2.0 L/min/m^2**
• **Minimum** flow-rates where suppression is achievable but firefighters may be exposed to longer duration fires and more punishing conditions.	**3.7 L/min/m^2**
• **Optimum** (adequate) flow-rates where control of the fire is achievable without unnecessary punishment to firefighters.	**6.0 L/min/m^2** (two dwelling rooms totalling $32m^2$)
Note: 'Optimum' means the absolute <u>minimum</u> amount required to extinguish a certain sized fire <u>effectively and safely</u>. A secondary safety (back-up) line of at least equal flows should always be provided in addition, in support.	**6.5 L/min/m^2** (commercial building fire 50-100m^2) **0.407 L/s/MW** (Grimwood) **0.385 L/s/MW** (Barnett)

Table 12.1: Benchmarks for firefighting water flow-rates can be determined in order to establish the level of risk to firefighters and the structure, caused by extended duration fires.

What does this mean to the Firefighter?

When deploying the initial attack hose-line into a fire compartment, it needs to be able to deal with the potential fire load existing in that room. The ideal water application will control fire before flashover or where travelling fire spread occurs. In some cases, fires will be fought internally as they burn at the peak of their heat release, which may last a few seconds or minutes. That peak in heat release can increase further still where windows fail or are vented.

During the initial attack in a compartment fire, a high-flow of water may extinguish the fire faster or a low flow may not be effective, or take longer to achieve control. In some circumstances a low flow rate will achieve control over a longer period of time, particularly where the rate of burning starts to slow down and decay as the fire load is depleted, but firefighters may be exposed to far greater thermal stresses over this longer duration.

In practice, we should aim to deploy the optimum amount of water in anticipation that a working fire may burn beyond the compartment of origin (47% of working fires) and apply enough water at an early stage to avoid longer duration fires, the potential for structural collapse and elements of increased building fire and smoke damage. A key statistic informs us that a room fires burn beyond the compartment of origin at one in every two 'working fires' in buildings. That's a fifty percent chance it will. A third of these *working fires* will also spread to involve other floor levels.

It would therefore be wise to consider if a 19mm hose-reel is sufficient for primary deployment into working building fires? It is also worth considering

here that 22mm high-pressure hose-reels can be twice as effective as 19m hose-lines in taking control of developing fires and the author, along with the Kent Fire and Rescue Service in the UK, has been leading the background research here since 1999.

Note: A 'working' building fire is defined as one where breathing apparatus is worn and firefighting water from a low or high-pressure hose-line is necessary to achieve control.

What does this mean to the Firefighter?

Fire-ground 'rule of thumb' fire-ground estimates –

When on-scene at a fire there are so many things a fire officer has to consider during the dynamics of a very fast-moving and stressful environment, such as that presented by a developing building fire. The calculation process must be easy to apply but be relevant and useful. As a Deputy Chief of the New York City Fire Department during the 1980/90s, Vince Dunn was experienced in commanding several serious high-rise fires in the city. His respected view was that a 2,500ft^2 (232m^2) fire on an open-plan office floor plate, was the largest size fire that his Manhattan firefighters could effectively deal with before control was lost and it would take at least one 63mm attack hose-line delivering 300galls (US)/min (1,134 L/min or 4.9 L/min/m^2 **of floor area fire) in order to do so. Such a high flow-rate demands a crew of 3-4 firefighters on the line to be able to deliver this fire stream into the fire floor.**

Another well-known US fire chief of the same era Bill Peterson (Plano Fire Department) further stated that based on his extensive practical firefighting experience, there would likely be a 50% failure rate **where firefighters are deployed internally to control a developing fire, once the fire development had surpassed 925ft^2 (86m^2) in floor space. These empirical observations from well-respected fire commanders of the time come very close indeed to the recent GCU research data outputs that are based on a large body of real fire experience in the UK.**

Based on the author's earlier research from 100 fires in London in 1989 and the GCU research described here, a series of rough fire ground rule of thumb guides were developed for UK national operational guidance (NOG) as follows:

- **Area of fire (m^2) multiplied by 5 (for fires involving between 100-500 m^2 of floor area)**
  A x 5 = required flow-rate (L/min) - (A = Area of floor in m2)
- **One low flow hand held fire stream (350 L/min) (say 100 galls/min) per 75 m^2 of floor area fire involvement**
- **One medium flow hand held fire stream (500 L/min) (say 125 galls/min) per 100 m^2 of floor area fire involvement**
- **One high flow hand held fire stream (750 L/min) (say 200 galls/min) per 150 m^2 of floor area fire involvement**

- **These flow-rates must be deployed as 'water on the fire', as compartment fires are most likely to develop and spread rapidly, at a rate of 22m²/min in an open-plan office (for example) – it may take several minutes following deployment into a large fire before water actually reaches the fire**
- **It has often been seen that a fast-growing fire in an open-plan floor area, or a vertically stacked fire load, can burn beyond the control of a single firefighting jet (hose-line) in less than 10 minutes (or far less on a vertical stack), once the flame reaches around a metre high from point of ignition.**

In figures 12.3 to 12.6, the outputs and engineering formulae for required flow-rates from the GCU research are displayed. The three finely dotted lines represent dwelling (houses and apartments) fires (lower); industrial and storage buildings (upper); and 'all other buildings' adjacent to the central line. Within the charts, the dashed line represents the flows calculated by the A x 5 rough fire-ground formula. It can be seen where that fits in with the more complex engineering formulae proposed by the research. Where the fire area is less than 120m² the fire-ground rule-of-thumb is inadequate and where fire areas >600m² it begins to estimate very high flow-rates. Therefore, the fire-ground formula A x 5 is only suited for use within the parameters as discussed above. Where deployment is for a fire area less than 120m², the minimum <u>target</u> flow-rate on any primary attack hose-line should be 200-500 L/min (1 or 2 x 22mm hose-reels) on high pressure or 350-500 L/min on low pressure. (Also, see guidance in chapter 3 – Fire Dynamics).

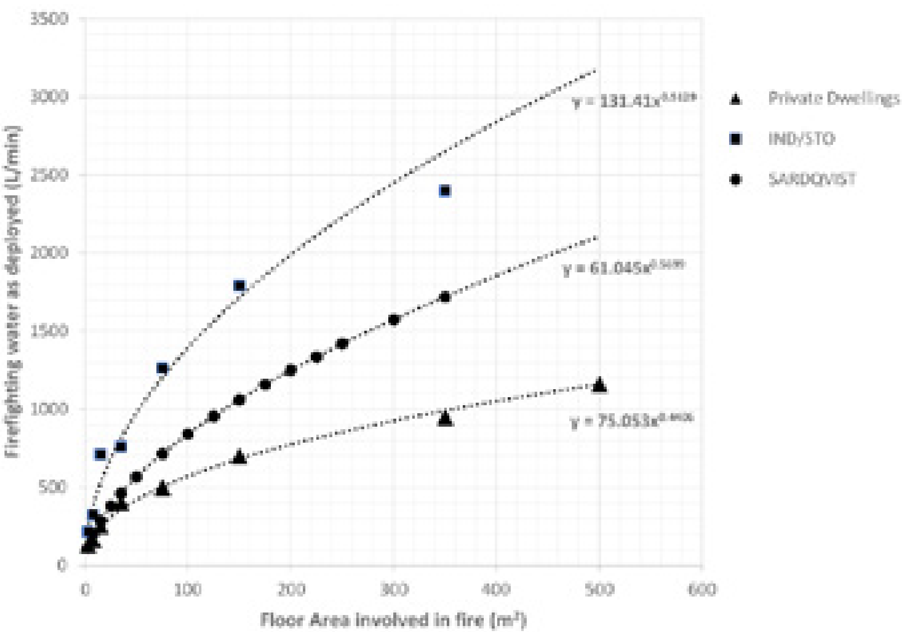


Figure12.3: Measured flow-rate from ,5401 building fires 2009-2012 - GCU Research

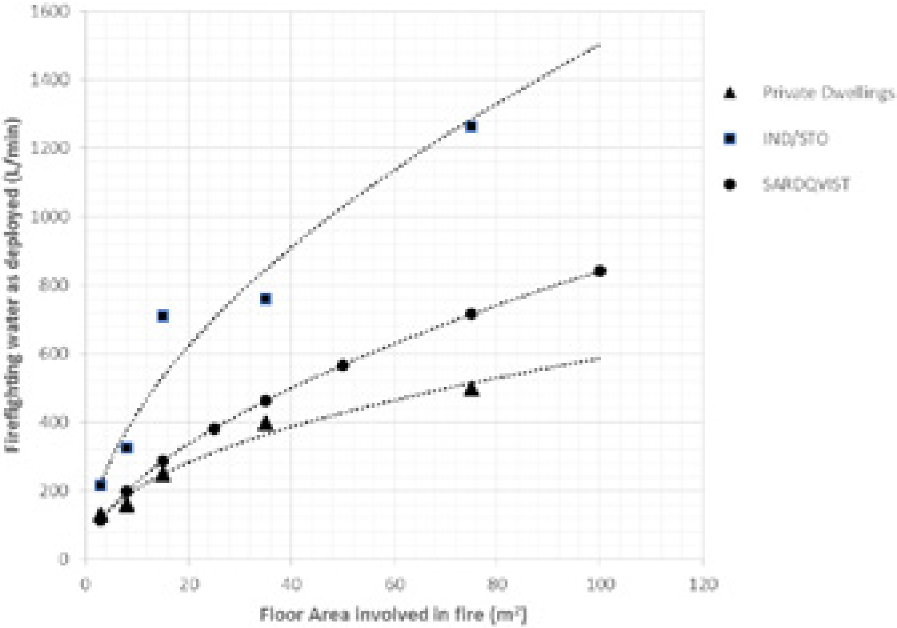


Figure 12.4: Measured flow-rate from 5,401 building fires 2009-2012 - GCU Research

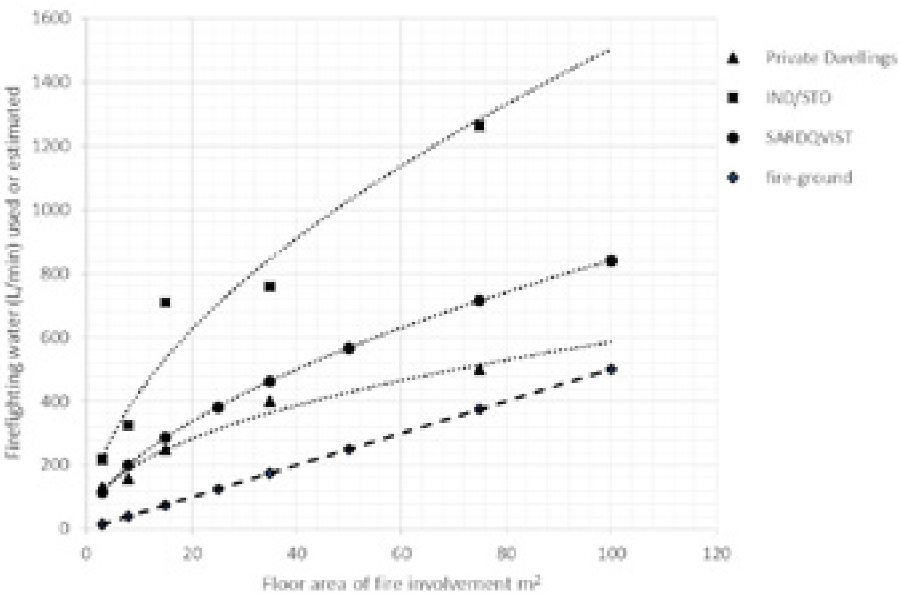


Figure 12.5: Fire-ground 'rule of thumb' flow-rate in comparison - GCU Research

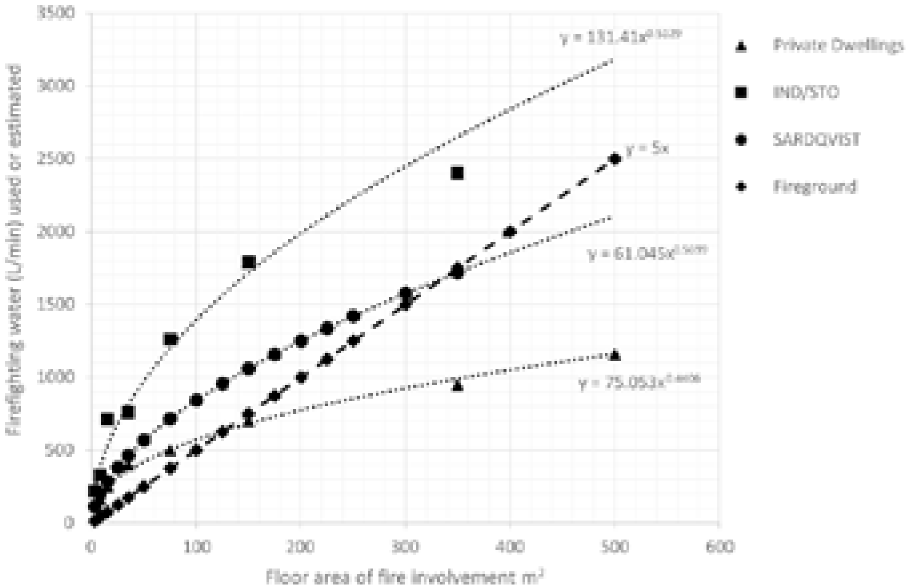


Figure 12.6: Fireground 'rule of thumb' flow-rate in comparison - GCU Research

12.3 THE THEORY OF FIRE SUPPRESSION USING WATER

Cooling Ratios

The cooling ratio of firefighting water is defined by the comparative percentages of applied water used or required to deal with fire in the gas phase (the volume of burning gases generally in the overhead but occasionally throughout a compartment) and fire in the fuel phase (generally fire across the surfaces of involved fuel at the fire's base).

It is natural that fire behaviour instructors will generally direct the greater proportion of their training in dealing with under-ventilated smoke, gases and fire in the gas-phase. It is rare that all firefighters are able to practice with fires in the fuel-phase or post-flashover, for the costs of repeatedly burning large amounts of carbonaceous fuels. Some will utilise LPG gas -fired simulators but these only present a false representation of controlling large amounts of fire and do not serve to teach firefighters how to fight fires. In turn, these methods of training create a dangerous bias in the mind-set of operational firefighters who generalise primarily in applying more water to the gas-phase than the fuel base in the belief that this will achieve greater suppressive effect in all instances.

Research (reported in 1979-1984) from several full-scale ventilation controlled fire tests at Karlsruhe University (Fire Research Station) in Germany revealed some commonality during the overall extinguishing process, where 36 percent of applied water was seen to suppress active (flaming) combustion, with the remaining 64 percent 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' of how firefighting water is actually applied.

Where fuel mass was lost at around 10.9 kg/min during a series of post-flashover fire tests heat release peaked at 3 MW in a room of 4 x 3m x 2.4m high, where the predicted energy release of 3 MJ/s (185 MJ/min) was only able to reach 92.5 MJ/min in the reaction zone due to ventilation limits (vent limited fire). The firefighters were able to control this fire in under two minutes using just 100 litres, with 35.7 litres extracting all the heat from the reaction zone at a rate of 2.59 MJ/litre (2.6 MJ/kg). The remaining 64.3 litres extracted around 246 MJ from the seat of the fire. With a fuel surface of about $40m^2$, this represents an application of about $1.6 L/m^2$ to cool the fuel base below its ignition temperature.

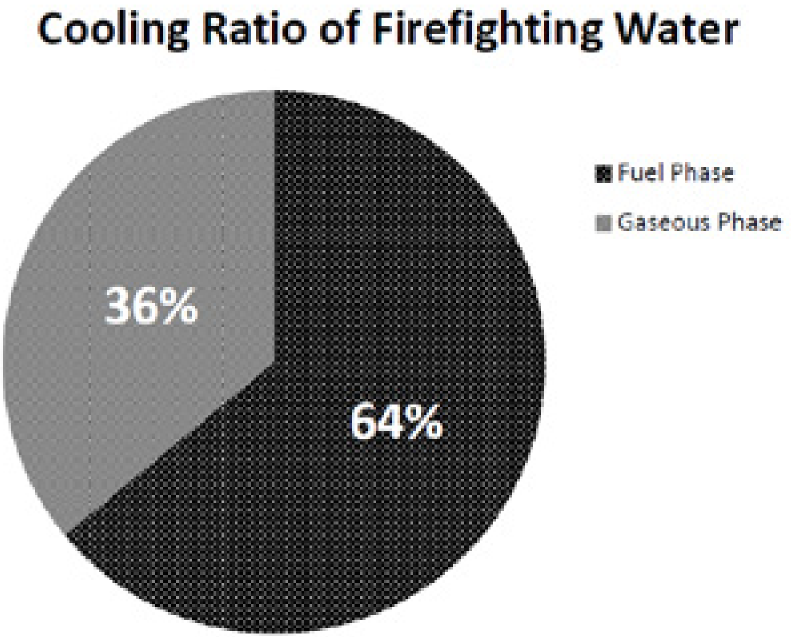


Figure 12.7: The ratio of cooling when using water applied into a fully-involved room fire is generically seen as 64%/36% fuel-phase/gaseous-phase, where neither approach is biased over the other.

In 1998, shortly following the deaths of three firefighters, UK firefighters began to receive 'fire behaviour driven' gas-phase suppression training, as taught in Sweden, beginning a twenty-year learning phase where the gas phase fire received far more attention than fire in the fuel phase. In retrospect and in reviewing the two fires where life losses occurred, it was certainly not a lack of knowledge of fire behaviour that killed those firefighters but more a lack of *tactical awareness*. Firefighting tactics play a greater part in firefighter life losses than fire behaviour knowledge, although admittedly the two are intrinsically linked.

If the reader believes that is not the case I suggest taking a close look at the prime casual factors in nearly all firefighter line of duty death (LODD) reports where:

- failure to apply early water on the fire base
- failure to effectively brief and debrief crews and act on information
- failure to communicate effectively with relevant parties on the fire-ground
- allowing moral pressure from bystanders to cloud situational awareness and prevent making logical tactical decisions
- disorganised self-deployments without directives (freelancing)
- failure to isolate fires by closing doors
- failure to carry out wind impact assessments prior to deployment
- mistimed and inappropriate tactical ventilation actions
- failures to maintain physical contact with crew members;

All of these clearly led the way in tactical omissions that contributed as prime causal factors in the majority of LODDs.

This is a most relevant point to bear in mind. It is also important to point out that the gas phase is generally of greater relevance to the firefighter in its *unburned state* as flammable fire gases will accumulate at the ceiling, in spaces and hidden voids. However, the fuel phase should always remain a primary concern when actually extinguishing a fire. Fire behaviour training should meet the objectives of practical fire dynamics by preparing firefighters to face the hazards of the gas phase in being able to identify dangerous conditions in a fire compartment or building. This training should also create situational awareness of the impact of venting a fire compartment or building. Finally, effective cooling of the gas layer to prevent a fire progressing to flashover should be taught.

At this point, there is some greater emphasis urgently needed in imparting adequate knowledge transfer of fire suppression in the fuel-phase. If this does not take place, then the bias in fire suppression will continue to prioritise gas phase over fuel base.

There are several examples of this:

1. At a high-rise fire in London the first crew in with a 45mm hose-line attempted to fight the fire by 'pulsing' water droplets into the gas layer but were unable to gain headway on an office fire involving a single work station. The actual work station was actually within reach of a high-flow smooth-bore stream applied from the stair but this was not available. The fire eventually spread to five floors and several firefighters had narrow escapes as they were overcome by the heat, as the fire rapidly developed.
2. At a residential high-rise fire in the UK, a team of firefighters attempting to reach trapped colleagues applied gas-phase flame cooling in an effort to make headway into the apartment. At this point one firefighter was believed to be still alive but the fire continued its development as the gas-phase attack took priority. A high-flow smooth-bore stream may have enabled progress to be made into the hallway. Tragically, there were two firefighter life losses at this incident.
3. Another residential high-rise fire south on the UK south coast saw a rescue team of firefighters trying to rescue four trapped firefighters by directing a 'pulsing' fog pattern into the burning gas layers when a high-flow straight stream pattern directed at the fuel base may have been far more effective. Two more firefighters tragically lost their lives at this incident.

It was engrained in the mind set of these firefighters through *fire behaviour training* to prioritise fire in the gas-phase over the fuel base fire during suppression operations. In both cases (2 and 3) the Coroner's investigations raised discussion points concerning the relevancy of training firefighters in this way.

What does this mean to the Firefighter?

Over a long period of time European firefighters have been taught quite rightly to be aware of smoke, heat and flaming combustion, particularly if transporting above their heads and behind them. This critical information can and does save lives. However, at the same time whilst working in fire behaviour training units, CFBTI's (compartment fire behaviour training instructors) have observed how the 1.5 Mega-Watt gas-phase training environment can be easily and most effectively controlled using very low flow-rates (even below 50 L/min). This has led to the development by some manufacturers to respond to a request for low flow 'fine droplet' hand-line nozzles.

This can be dangerous!

It will be demonstrated later where the heat release rates and speed of fire development that can be expected in small room to corridor fires, and larger open-plan compartments, can rapidly outpace low flow nozzles at an early stage, most particularly as the 'energy efficient' building fire environment evolves.

Where a fire's fuel base is not immediately accessible or observed, shielded by walls, furniture or in voids, the gas phase becomes the priority and low-flow fine droplets will perform best. However, where the fire's fuel base may be reached by bouncing a mid-high flow stream off the ceiling, a wall, or more importantly with a direct application, then this approach should be used.

Prioritising training and equipment and then procedural protocols, to bias one method of firefighting over the other (gas phase/fuel phase), is ineffective and potentially negates a risk based approach to interior firefighting.

Note: This evidence based guidance does not apply to the use of fog insertion tools from external locations to the fire compartment.

Extinguishing Efficiency

The theory of fire suppression has been studied and researched by practitioners, scientists and academics for several decades. However, in practice the efficiency of water as a heat sink is usually determined by the application technique, as water that fails to reach the seat of the fire cannot contribute to its ultimate extinguishment. In typical firefighting sprays, for example, only a small fraction of the relatively large droplets in the delivery will realise their maximum heat extraction potential through evaporation, while the majority will remain in the liquid phase and form runoff. Conversely, if the water is delivered in the form of very fine droplets with the aim of promoting rapid evaporation, the horizontal application of the spray may not possess the momentum required to penetrate the flame. The net result is that water is wasted and firefighting efficiency is compromised. If ultra-high-pressure (UHP) water droplets are used, they may have some greater cooling effect as the momentum will carry the finely divided droplets further.

So too is there generally some major water run-off when firefighting water is delivered directly onto a burning fuel base. Estimates in research have placed this efficiency of applied firefighting water at around 30-50 percent. That is, for every 100 litres applied, only 30-50 will take part in the suppressive and cooling phase, with the remainder possibly finding its way onto the floor and out of the structure. Researchers have broken this down to 35 percent efficiency when applied into the fuel base and 15 percent efficiency when applied into the gas-phase (total 50 percent). Research by Rasbash suggested primary efficiency factors that conform to later work by Barnett in producing a cooling efficiency factor.

What does this mean to the Firefighter?

As you apply water to a confined room fire, probably only half of the water from a firefighting stream will reach the fire and evaporate. The rest will 'run-off'. Where a fog pattern is applied effectively there will be less run off as most water will evaporate. However, getting a fog pattern to strike the base fire is not always easy or effective and a straight or solid stream is more often needed to penetrate into, and cool, the burning items. Pump operators must learn to optimise their water supply, working in flow-rate (L/min) as well as pressure in providing adequate water to the hose-lines in operation. Too much pressure at the nozzle may create a hose-line that is difficult to handle but too little water may place firefighters at great risk. It is important to get the balance right. Smooth-bore nozzles can flow more water for less pressure and should be considered in some circumstances, particularly where heavy fire is likely.

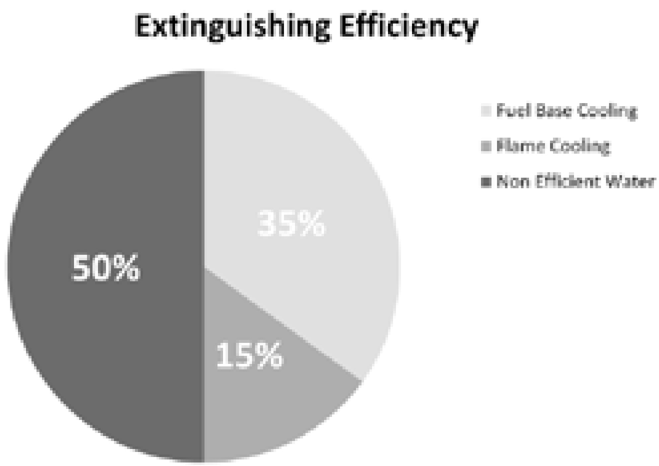


Figure 12.8: The widely accepted extinguishing efficiency of water applied into building fires.

The theoretical cooling effect of water can be calculated using specific heat capacity and latent heat values. 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.

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

This means that to transform 1 kg (1 litre) of water at 10˚C to steam at 600˚C, an energy input of **(0.38 + 2.26) + (600-100 x 0.002) = 3.6** MJ is needed. The heat absorption capacity is therefore 3.6 MJ per kg of water, used to its maximum at 600˚C.

Note: The specific heat of steam is 0.002 MJ/kg at 100°C and 0.006 MJ/kg at 300°C, so an average could be used, based on steam tables. If water were applied into a 300°C gas layer as opposed to 600°C, according to the above calculations an energy input of 3.04 MJ is needed. The heat absorption capacity would then be just 3 MW.*

Cliff Barnett's research 2004:
(A computer analysis based on data from Grimwood's 100 fire study in 1989)

It is also pointed out that the combustion efficiency of a confined fire almost never reaches 100 percent inside the compartment. Fig.12.9 illustrates the changes a building fire goes through as it grows in size. Barnett[135] informs us that 'when a small fire first ignites in a building, the air supply will be in excess and the airflow ratio will be between 2 and 3 (fuel control), at say near point B. As the fire grows in size, the relative airflow ratio falls to the point where the air supply is controlled by the size of the available openings (ventilation control). The airflow ratio decreases with increasing fire size from B to C to D and finally finishes up somewhere between D and E. Only for a small part of the growth will the fire efficiency be close to the suggested conservative design value of k_F = 0.50. After growth is completed, the fuel efficiency factor could well lie between E and D, or between 0.15 and 0.45 for the remainder of the fire duration'.

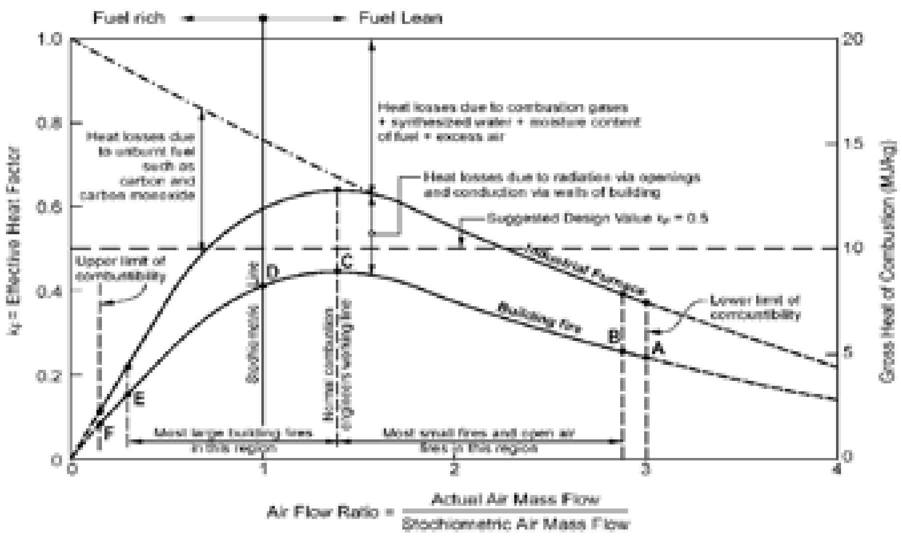


Figure 12.9: Combustion diagram for a typical air-dry wood fuel showing relationship between gross heat of combustion and air-flow. For a building fire, the effective heat coefficient k_F rarely exceeds 0.45 thus a k_F value of 0.50 can be considered a conservative and upper limiting value for design purposes. ***(Reproduced from sfpe-TP2004-1, Barnett.C)***

135 Barnett.C, SFPE (NZ) Technical Publication – TP 2004/1

In combining the efficiencies of firefighting water applications with combustion efficiency Barnett uses the following formula:

$$F = \frac{k_F * Q_{max}}{k_w * Q_w} \qquad \textbf{\textit{Eq.12.1}}$$

Where

F required firefighting water flow in l/s

k_F heating efficiency of fire (conservatively 0.50)

k_W practical cooling efficiency of applied water (conservatively 0.50)

Q_{max} maximum heat output of fire in MW

Q_W theoretical absorptive capacity of water at 100°C = 2.6 MW/l/s

Or alternatively a re-arrangement of Equation 12.1, to calculate the heat absorption (MW) of the water used for suppression:

$$Q_s = \frac{F * (k_w * Q_w)}{k_F} \qquad \textbf{\textit{Eq.12.2}}$$

Where

Qs The heat absorption (MW) of the water used directly on the fire for suppression

F delivered firefighting water flow in l/s

In simple terms this means that for each MW of Q_{max} in a real fire, according to Barnett the firefighting water flow will need to be 0.50 / (0.50 x 2.6 MJ/kg) = 0.38 L/s/MW or 23 L/min/MW of Q_{max} (the point of peak heat release).

Paul Grimwood's Research[136] (based on 5,401 'working' Building Fires 2009–2012)
Glasgow Caledonian Fire Engineering PhD research 2015

Benchmark research by Rasbash (the 'fire point' theory), supported in later work by Beyler, demonstrated that for diffusion flames of dimension 5-60cm, removal of about 30-35% of the heat of combustion from within the reaction zone would cause the flame to be extinguished. This indicates that for diffusion flames in the combustion zone (gas-phase), the theoretical absorption capacity (3.6 MJ/kg) should be multiplied by a factor of 3.3 (3.6 x 3.3 = 11.9 MJ/kg) to obtain the extinction capacity. Therefore, in theory one L/s of water may absorb 11.9 MW of heat release in the combustion zone.

The following approach by Grimwood (Equation 12.3) demonstrates very close correlation with Barnett's equations given above and is further validated by the data outputs from the 5,401 building fires in the GCU research at. It is observed that by combining Rasbash's fire point theory with the full-scale fire tests undertaken by Karlsruhe University (above) – for a flow of 1 L/s the total **heat absorption** capacity (per Mega Watts) of firefighting water is –

136 Grimwood.P, A study of 5401 UK building fires 2009-2012 comparing firefighting water deployments against resulting building fire damage, Ph.D thesis 2015, School of Engineering and Built Environment, Fire Risk Engineering, Glasgow Caledonian University Scotland, United Kingdom 2015

$$\textbf{MW}\text{ (heat absorbtion)} = (W_{gas} * E_{gas} * 3.3 * L/s * 0.15) + (W_{fuel} * E_{fuel} * L/s * 0.35) \qquad \textbf{Eq.12.3}$$

Where

W_{gas}	=	Percentage of water applied into the gas phase	
W_{fuel}	=	Percentage of water applied into the fuel phase	
E_{fuel}	=	An energy input of 2.6 MJ/kg is required to vaporise 1 kg of water at 100°C when applied onto the fuel-phase	
E_{gas}	=	An energy input of 3.6 MJ/kg is required to transform 1 kg of water at 100°C to steam at 600°C when applied into the gas-phase – *If water were applied into a 300°C gas layer as opposed to 600°C, according to the above calculations a lesser energy input of 3.04 MJ is needed. The heat absorption capacity would then be just 3 MW.*	
3.3	=	An efficiency factor based on the Rasbash 'firepoint' theory	
0.15	=	The practical efficiency factor of water applied in the gas phase	**50% Total efficiency**
0.35	=	The practical efficiency factor of water applied in the fuel phase	
L/s	=	The quantity of water applied into the fuel or gas phase in Litres/sec.	

When advancing hose-lines internally firefighters will utilise a range of fire stream applications and techniques that include narrow and wide angled spray patterns to protect themselves from heat and smoke and direct combustion products away from their position. Locating the fire base in limited visibility and accessing the fire when it is shielded also create difficulties. Short bursts of water-fog may be used to suppress fire and cool heat in the hot gas layer and then eventually water will be directed at the fire's base to complete suppression. It is therefore virtually impossible to apply water in an optimal way during real firefighting operations and this means that one litre of water will rarely achieve its theoretical cooling potential.

There have been several attempts to generate a range of formulae by which generic firefighting water demands at building fires can be calculated, based on a theoretical analysis of water's cooling properties, or through empirical research of real fire data. In some models, both of these approaches have been combined.

However, these models or building design guides often promote a wide variance in recommended firefighting 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 firefighting techniques limit the use of resulting formulae. In other cases, the source data is inappropriate or the methodology itself is incomplete, or is structured without any in-depth validation.

Many of these models base their formulae on a 0.3 water application efficiency factor which supports laboratory or experimental research, whereas others utilise empirical fire flow data obtained from actual building fires. The methodology below is based on a 0.5 water application efficiency factor (k_W at 50 percent effective), derived from an existing computer analysis of 100 building fires in London (1989)[137] and further validated by the GCU County/Metro research of over 5000 UK building fires occurring between 2009-2012.

In terms of application efficiency, Grimwood can attest to a range of situations and variable dynamics affecting flow-rate performance where access to the fire base was difficult or the distribution of the fuel load led to more energy being released into the gas-phase. In some instances firefighters would apply large amounts of water into smoke because they were guided by sounds as to where the base of a fire is likely to be. In these situations the water run-off was high and the efficiency was low. On other occasions the 'air' appeared to be burning, visibility was good and spray patterns of water droplets were directed into the burning gas-

137 Grimwood. P, Fog Attack, FMJ Publications, Redhill Surrey, UK 1992

phase with great efficiency and less run-off. In some stair-shaft fires where the base and head of the stairs were vented, the chimney effect was ideal for approaching the fire from below. Using short bursts of finely divided droplets in a spray pattern, the natural buoyancy of the fire transported the water droplets up higher into the stairs and vast quantities of steam exited the high-level vent, extinguishing fire all the way. In such cases the water run-off was almost zero and the efficiency was close to 100%. However, a generic approach is used to calculating water application efficiency overall.

The GCU research was very pragmatic in its approach to estimating the actual amounts of firefighting water used to control building fires but recognised the need to establish a theoretical foundation in support of the data.

Calculating 'adequate' firefighting water flow-rate (Grimwood Eq.12.3)

- According to Grimwood (Eq.12.3), the ('real fire') heat absorption of water at 1 Litre/second = 2.46 MW per L/s – (0.407 L/s/per MW at peak HRR)
- Or; 24.42 L/min/MW of Qmax (the point of peak heat release) is required to achieve control and suppression of building fires, which closely correlates with Barnett's calculation of 23 L/min/MW.

Flame Suppression (36%)	0.36 x 3.6 x 3.3 x 1 x 0.15		= 0.64 MW
Fuel Base (64%)	0.64 x 2.6 x 1 x 0.35		= 0.58 MW
		Total	= **1.23 MW**
		Q_s	= 1.23 / 0.5(k_F)
			= **2.46 MW** *per L/s*
			= 1 / 2.46
			= **0.407 L/s/MW**

Note: Q_s = the heat absorption (MW) of the water used directly on the fire)
K_f = the combustion efficiency taken as 0.5 (50 percent efficiency)

Example One:

19mm HP Hose-reel tubing x 54m at 1.83 L/s

Flame suppression 0.36% x 3.6 MJ/kg x 3.3 x 1.83 L/s x 0.15		= 1.18 MW
Fuel base cooling 0.64% x 2.6 MJ/kg x 9.16 L/s x 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:

Smooth-bore 22mm nozzle at 9.16 L/s

Flame suppression 0.36% x 3.6 MJ/kg x 3.3 x 9.16 L/s x 0.15		= 5.93 MW
Fuel base cooling 0.64% x 2.6 MJ/kg x 9.16 L/s x 0.35		= 5.33 MW
	Total	= 11.26 MW
	Q_s	= 11.26/0.5(k_F)
Total heat absorption capacity		**= 22.5 MW**

What does this mean to the Firefighter?

All these calculations lead to one conclusion. There is always going to be a large amount of water from your firefighting stream that ends up on the floor, particularly if the fire is predominantly involving dense fire loads, furniture, items and heavy solid combustibles. Where the water is applied into large amounts of gaseous flaming combustion, the drop-out may be far less, depending on droplet size and velocity as it exits the nozzle. In general, we apply a fifty percent overall efficiency factor to your applied firefighting water stream, which means half the water applied goes to waste.

Couple this with a calculated heat absorption capacity (Mega-watts or MW) and we can see how effective your hose-line flow-rate is likely to be on a certain sized fire:

Nozzle	**Water Flow-rate (L/s)**	**Water Flow-rate (L/min)**	**Heat Absorption Capacity (MW)**
Smooth-bore 14mm	4.83	290	11.9
Smooth-bore 22mm	9.16	550	22.5
Smooth-bore 22mm	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 <1mm water droplets	5.0	300	12.3
LP Fog Nozzle <1mm water droplets	7.91	475	19.4
19mm HP Hose-reel tubing x 54m**	0.75	45	1.84
19mm HP hose-reel tubing x 54m**	1.83	110	4.5
22mm HP hose-reel tubing x 54m**	3.3	200	8.1
25mm HP hose-reel tubing x 54m**	4.16	250	10.2

Table 12.2: Minimum needed flow-rates for suppression based on heat release rate (HRR) at ***2.46 MW per L/s*** *(ref: Grimwood Eq. 12.3).*

**** The use of UHP pumps may increase stream velocity, reduce water droplet size, and can increase suppressive capacity in the gas-phase by up to 3.5 times, when compared to low pressure streams at the same flow. However, where the fire growth rate is rapid, or where the fire load is heavy (or the structure becomes the fire load), the low flow-rate may then expose firefighters to dangerous levels of thermal exposure**

An important point to note is, that even though water applied into the flaming gaseous phase might appear an effective use of the limited amount of water

available at the nozzle, its low overall efficiency of just 15 percent **is founded in the fact that although far less water is required to cool flaming fire gas layers, somewhere between two and six times more water will be needed at that same nozzle to finish the job by controlling the fuel base fire. Therefore, in practice, a 40 L/min nozzle that is effective in the gas-phase of a particular sized fire is likely to require at least 80-250 L/min in order to deal safely and effectively with the fuel base fire.**

12.4 THE AMOUNT OF FIREFIGHTING WATER USED BY FIREFIGHTERS

A detailed analysis of 100 serious building fires in London was undertaken by the author in 1989 where, as a London Fire Brigade fire investigator, attendance was made at each fire to record the extent of fire damage and the flow-rates needed to control the fires. The primary objective of this research was in support of finding a practical method that fire commanders could use at the scene of fires to estimate the quantities of water needed to control fire spread. The outcome from this limited research demonstrated that target flow-rates of 4 L/min/m^2 of fire involvement (fire damage) would normally suffice for building fires where the fire was vent controlled and vent openings were limited. Where fires were well vented and approaching fuel-controlled conditions, a minimum flow-rate of 6 L/min/m^2 was recommended. Although this research covered a limited number of working fires in London, the recommended flow-rates were very close indeed to later research, again carried out by the author between 2009-2012, where 5,401 fires were again studied for the amounts of firefighting water used by firefighters to control developing fires in buildings, where the fires were so serious that breathing apparatus was required.

This research data was drawn from fires in two fire brigade areas, one a county brigade of 3,544 km^2 and a Population Density of 413 people/km^2 where 1,152 working Fires occurred over a three-year period; and a city metro brigade of 1,276 km^2 with a Population Density of 2,105 people/km^2 that had 4,249 working Fires over the same period. To achieve greater accuracy, much of the data was retrieved direct from the fire-ground to computer terminals monitoring actual flows used with water-smart technology vehicle pump flow-meters.

These fires involved all building types ranging from residential dwellings, high-rise apartments, hotels, shops, restaurants, schools and care homes to very large industrial units and warehouses. Six hundred of these fires (11 percent of the total) involved fire damage exceeding 50 square metres and a further 1.3 percent of fires involved fire damaged floor areas exceeding 500 square metres. The average fire sizes ranged between 16m^2 of floor area for residential dwellings up to 95m^2 for industrial units, with all other building and occupancy types somewhere in between. For these fires, firefighting water flow-rate densities ranging between 8-12 L/min/m^2 of fire involvement were used to achieve control. In total, 65% of all building fires in the GCU research (86% of fires that just used high-pressure hose-reels) were extinguished using just the 1800 litres carried on-board.

Using data from the UK National Incident Recording System (IRS) the data for 5,401 building fires occurring in two UK fire authorities between 2009–2012 are presented below under a list of 'purpose groups', according to the UK building regulations (table D1 2007 version). The data is also listed under 'County' and Metro' fire service areas for comparison.

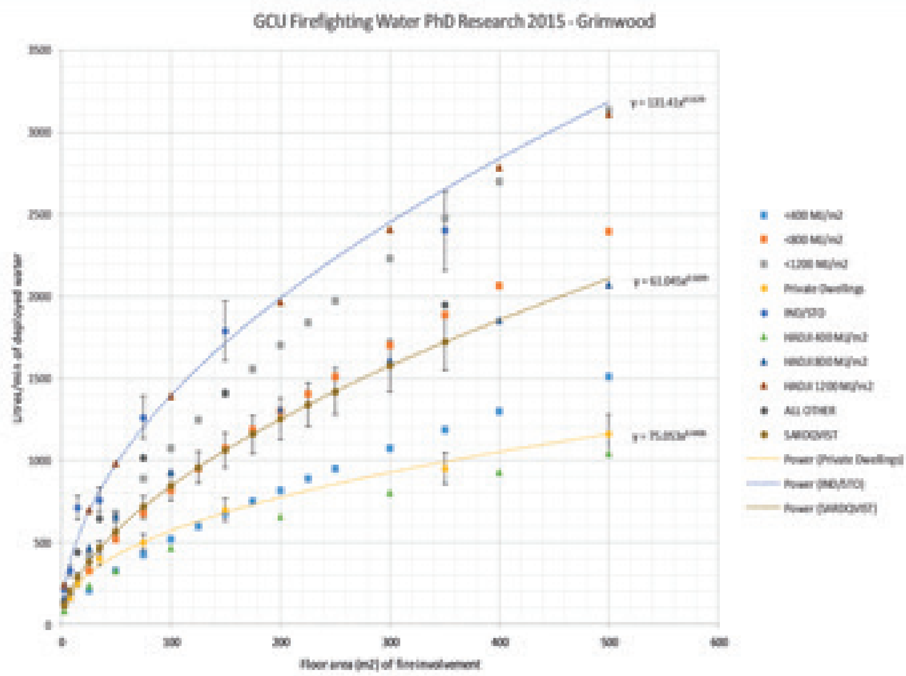


Figure 12.10: 10% error bars are added to the author's GCU research for consideration. Also shown in the chart are the firefighting water flow-rate data taken from other notable research by Cliff Barnett (squares), Stefan Sardqvist, and Hadjisophocleous, G.V. & Richardson, J.K. (triangles) (at 50% applied water efficiency).

The building fires were all considered 'working fires' where a recordable area of fire damage occurred and water was flowed internally by firefighters wearing breathing apparatus. The research did not include exterior fires, exterior roof fires, derelicts buildings or chimney fires. The data is validated in part by water-smart flow meter technology that records actual flows used by pumping appliances (fire engines) at fires.

The purpose groups listed are as follows:

- **Dwellings** (private houses, apartments and flats)
- **Residential (institutional)** (Hospitals; Homes; schools; prisons)
- **Residential (other)** (Hotels; colleges; hostels; halls of residence)
- **Assembly & Recreation** (Public entertainment; conference; museums, churches; law courts; health centres; day centres; clinics; passenger terminals)
- **Offices**
- **Shop & Commercial** (retail)
- **Industrial** (Factories)
- **Storage and other non-residential** (Storage warehouses and car parks)

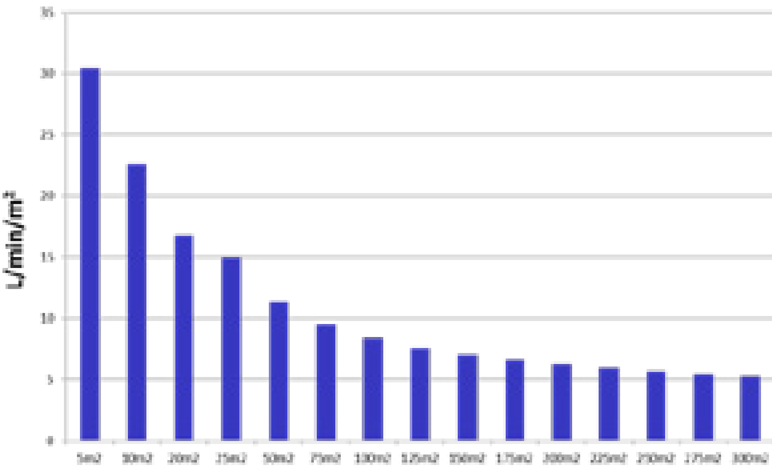


Figure 12.11: Typical flow-rate densities recorded for fires in occupancies demonstrating medium fire loads

12.5 BUILDING FIRE DAMAGE AND FIREFIGHTING WATER FLOW-RATE – THE LINK

The GCU data demonstrated average fire sizes of 38.78m² in County and 30.33m² in Metro areas and showed that fires in the Metro area were less likely to spread from the room or floor of origin and were less likely to result in multi-floor fires.

In comparison to UK fire spread statistics (2001-2011) from the Department of Communities and Local Government (DCLG), this research data of 5,401 working fires (2009-2012) presents a different picture from the DCLG representation of fire containment where it is seen that 86 percent of fires are contained within compartment of fire origin. According to the County/Metro research, when a building fire requires firefighters to deploy hose-lines and wear breathing apparatus, only 53 percent of fires are confined to the compartment of fire origin and fire spread to other floors within a building occurred at a quarter of fires in the Metro area and more than a third of the County fires.

It was noted that once fires had burned beyond 500m² of floor space, the buildings were generally lost completely. Building fires in this research were also broadly seen to spread beyond the compartment of origin more often (48%) than annual government statistical reports would suggest (8%), as these were all 'working' fires' and not simply just 'calls' to fires.

It was a further observation of the research that the building fire damage (fire containment) in the metro fire area was less than in the county area. This was interesting as both fire services applied exactly the same total firefighting flow-rate density at 12 L/min/m² of fire damage across the total number of fires. However, the metro fire service delivered a higher flow-rate during the very early stages following arrival on-scene than the county fire service did. This caused the county fire service to apply greater amounts of water during the later stages of firefighting to achieve control. It is suggested that this is why the building fire damage was greater in the county area. It appears that greater amounts of resources, staffing and flow capacity is needed later in a firefighting operation if the water flow-rate is inadequate from the outset.

The County fire service deployed nearly twice as many lay-flat attack hose-lines later in the fires to deliver the same final quantity of water as Metro, requiring greater resources overall.

Glasgow Caledonian University Research of 5,332 UK Building Fires 2009–2012

COUNTY	Occupancy	Incidents	L/min/ m^2	Average Fire Size m^2	ROOM %	FLOOR %	MULTI-FLOOR %	19mm HP H/ REELS %
	Dwellings	839	13.84	16.82	61.74	16.69	21.57	92.37
	RESI INST	24	8.34	36.7	70.83	8.33	20.83	84.5
	RESI OTHER	43	8.92	29.3	39.53	18.6	41.86	81.4
	ASSEMBLY	72	11.93	33.38	49.32	16.44	32.88	82.33
	OFFICES	23	19.54	15.13	60.87	4.35	34.78	81.96
	SHOPS	107	17.55	22.86	56.07	17.76	26.17	77.31
	INDUSTRIAL	35	9.59	62.68	54.29	8.57	37.14	50.29
	STORAGE	9	6.3	93.44	11.1	22.2	66.67	33
	TOTALS	**1152**	**12.00**	**38.78**	**50.46**	**14.11**	**35.23**	**72.89**
METRO	**Occupancy**	**Incidents**	**L/min/ m^2**	**Average Fire Size m^2**	**ROOM %**	**FLOOR %**	**MULTI-FLOOR %**	**19mm HP H/ REELS %**
	Dwellings	2939	12.18	15.72	67.68	15.75	16.57	93.81
	RESI INST	27	18.71	6.92	74.07	18.52	7.41	92.88
	RESI OTHER	72	18.74	12.59	54.17	11.11	34.72	87.83
	ASSEMBLY	300	12.22	19.24	64.67	17.33	18	89.67
	OFFICES	66	7.96	39.77	54.55	10.61	34.85	89.79
	SHOPS	459	10.48	30.17	44.66	27.45	27.67	84.39
	INDUSTRIAL	288	9.61	51.00	46.53	26.39	27.08	59.39
	STORAGE	98	9.72	67.27	42.86	31.63	25.51	45.9
	TOTALS	**4249**	**12.45**	**30.33**	**56.14**	**19.84**	**23.97**	**80.45**

Table 12.3: The response data from two UK fire services (County & Metro) were analysed over a three-year period for building fires where breathing apparatus was used and water was flowed to achieve fire control. All fires in the table involved less than 500m^2 of fire area – there were 69 further fires in the research that were larger than 500m^2.

Key

Group	Purpose Groups according to the UK building regulations
m^2	area of fire damaged floor space in square metres
L/min	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 60m x 19mm rubber tubing first-strike firefighting hose @ 100 LPM

Note: Hose-reel data displayed separately – overall 65% of **total fires** were dealt with using tank water without augmenting the supply (87% of **hose-reel fires** used tank water only) 13% of fires required additional firefighting water augmented from other sources.

During this period, there were 70 additional large building fires involving 500 – 10,000 sq/m of fire damage

What does this mean to the Firefighter?

It pays to pre-plan the firefighting water flows that can be immediately available to firefighters on arrival and therefore 'adequate' firefighting water becomes a key factor in the entire response and deployment model. It has also become clear that it is often those in a position to harness such changes within the fire service response model who fail to understand or appreciate the technical aspects associated in meeting an adequate flow-rate provision (L/min) and matching this against the building risk profile (fire load) in the area served.

The evidence show, quite simply, that less water applied from the outset of operations usually means more water, hose, staffing and resources are needed later on in an incident. Add to this the suggestion that building fire damage increases at 48 percent of working fires, as fires spread beyond the room and even floor of origin, wherever first response water deployments are inadequate.

The data also demonstrated that fires in the Metro area were less likely to spread from the room or floor of origin and were less likely to result in multi-floor fires. In comparison to UK fire spread statistics (2001–2011) from the Department of Communities and Local Government (DCLG), this research data of 5,401 working fires (2009–2012) presents a different picture from the DCLG representation of fire containment where it is seen that 86 percent of fires are contained within compartment of fire origin. According to the GCU research, when a building fire requires firefighters to deploy hose-lines and wear breathing apparatus, only 53 percent of fires are confined to the compartment of fire origin. It was further noted that fire spread to other floors within a building at a quarter of fires in the Metro area and at more than a third of the County fires.

The primary means for distribution of delivered water flow-rate (Fig.12.15) varied between the two fire services in the research where the county utilised main lay-flat hoses to deliver 57 percent of their firefighting water but only 43 percent when using high-pressure 19mm hose-reels. In contrast, the metro used less lay-flat hose but more hose-reels to deliver the same average quantity of water density as the county across all building fires. This research data from GCU suggests that applying greater flows (L/min/m^2) from the outset may lead to less building damage and a reduced staffing/resource requirement during the latter stages of firefighting.

Continued overleaf.

	County	%	Metro	%
Fire Incidents	1116		4573	
Total reels & jets laid	1822		6459	
Jets/reels	466/1356		1069/5390	
Fires just Hose-reels	813		3682	
Reels laid	915		5058	
Reels off tank supply	746@702 fires	86.35	4170@3205 fires	87.05
Reels Augmented	164@107 fires	13.16	888 @477 fires	12.95
Just Jets	78 Jets @ 35 fires		745 Jets @366 fires	

County	Metro
1116 fires/1822 hose-lays – 1.63 per fire	4573 fires/6459 hose-lays – 1.41 per fire
1116 fires/1356 reels laid – 1.21 reels per fire	4573 fires/5390 reels laid – 1.17 reels per fire
1116 fires/466 jets laid – 1 jet per 2.4 fires	4573 fires/1069 jets laid – 1 jet per 4.27 fires
Just reels dealt with 72.85% fires	Just reels dealt with 80.5% fires
Just reels – 1.12 reels laid per fire	Just reels – 1.37 reels laid per fire
1.06 reels off tank supply only – per fire	1.3 reels off tank supply only – per fire
1.53 reels of augmented supply – per fire	1.86 reels of augmented supply – per fire
At 3.14% fires 'just jets' were used	At 8% fires 'just jets' were used

813 FIRES JUST REELS		3682 FIRES JUST REELS
7.72m²	Average Fire Size	11.14m²
3.2MW	Estimated HRR @ 15–20% vent – one door	3.9MW
14.73 litres/min/m²		12.36 litres/min/m²
Room of origin – 591 (72.7%) Floor of origin – 118 (14.5%) Spread to other floors – 114 (14%)	**Fire Confinement and Fire Spread**	**Room of origin – 2621 (71.2%) Floor of origin – 601 (16.3%) Spread to other floors – 460 (12.5%)**

Table 12.4: Fire suppression data – GCU research (includes fires in derelict buildings)

12.6 OTHER MOST RECENT RESEARCH INTO FIREFIGHTING WATER FLOW-RATES

Fire Protection Research Foundation (NFPA)

A review of nineteen international firefighting water flow methodologies 2014

A review of nineteen international fire flow methodologies, including the author's 1989

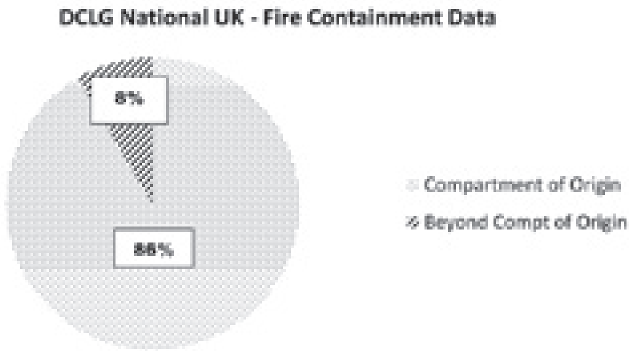


Figure 12.12: Nationally recorded (UK) levels of fire spread or fire containment for all building fires (Note: 6% of these fires spread beyond the building of origin) (Many of these fires were recorded in the national incident recording system as 'no action' by fire service) ***Source: Table 4 of UK Fire Statistics (DCLG) 2001-2011.***

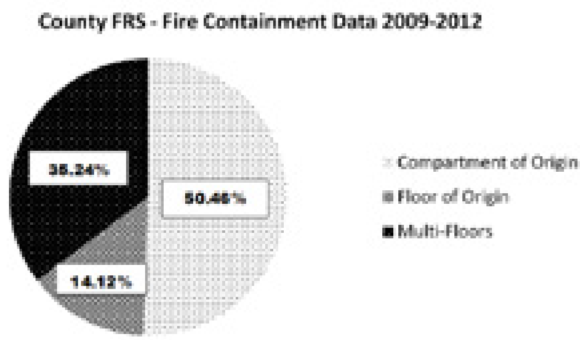


Figure 12.13: Levels of fire spread or fire containment in the County Area (1,152 working fires)

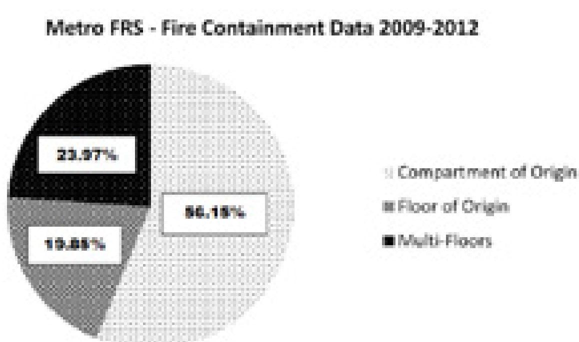


Figure 12.14: Levels of fire spread or fire containment in the Metro Area (4,249 working fires)

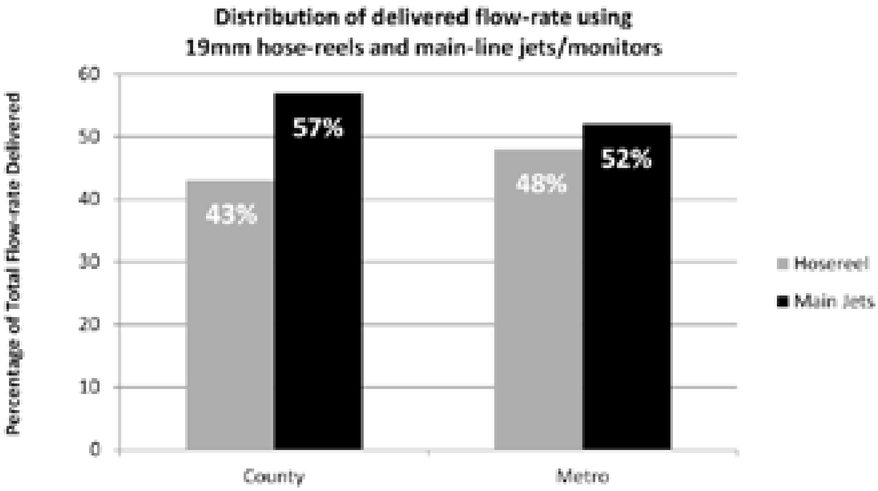


Figure 12.15: How the two fire brigades (County and Metro) delivered their firefighting water in the GCU 5,401 building fires (hose-reel versus main jets).

research (described as the 3D method), was undertaken on behalf of the NFPA's research foundation in 2014. The review demonstrated a wide variance in calculated fire flow requirements. This was visibly apparent, particularly where calculation processes were aimed at (a) infrastructure planning, (b) building design or (c) 'easy to use' on-scene firefighting calculation in support of fire service intervention. Planning methodologies supporting piped hydrant grids based on applied risk profiles resulted in the highest flow demands, followed by individual building design needs and then on-scene fire attack methods.

Of the sixteen methods used for comparative purpose, only four utilised the heat release rate as a means of assessing needed flow-rates and only three methods linked an *efficiency factor* of applied water. The SFPE (NZ) TP 2004/1 (Barnett) methodology (detailed at 12.3 above) was the only one to link both HRR, and water application efficiency factors derived from empirical research.

Stefan Sardqvist's Research 1998[138]:
(A study of Research into 307 Non-residential Fires in London 1994-1997)

Stefan Sardqvist undertook some detailed research into 307 fires in non-residential buildings in London from 1994 to 1997 and this research has since been widely referenced for flow-rate input data in subsequent firefighting water models globally. The fires in this study were relatively limited in size where just seven of the incidents exceeded 100m^2 in fire damaged floor area. The data refers solely to fires in public and commercial premises, schools and hospitals, industrial premises, and hotels and boarding houses. The data suggested that the upper limits of fire service intervention appeared to be about 50m^2 for a two-pump incident (2 fire engines) and 100m^2 for a four-pump incident (4 fire engines). The resulting Sardqvist formula to calculate needed flow-rate produces quite reasonable correlations for the applicable range of buildings when compared to the GCU County/Metro research in a single line flow-curve.

138 Särdqvist. S; Real Fire Data; Fires in non-residential premises in London 1994-1997; Report 7003 Lund University

Hadjisophocleous & Richardson 2005[139]

A validated methodology for calculating adequate flow-rate

A further theoretical methodology that appears to enhance the existing Canadian NRC FIERA model is presented by **Hadjisophocleous & Richardson** and allows the fire engineer to input any particular chosen extinguishing efficiency factor (kw) in the calculation process, (as does Barnett's). However, when Barnett's 0.5 extinguishing efficiency factor is used as an input (kw) to Eq.12.5, the outputs from this method compare well with that proposed by Barnett and also show reasonable correlation with the GCU County/Metro research real fire data, although not quite so where the floor plate is large.

In the development of Eq.12.5 the 50 percent combustion efficiency input proposed by Barnett is already included. Also, included in Eq.12.5 is work by P H Thomas in 1959 (Eq. 12.4) where an attempt to draw a relationship between horizontal fire area and time to fire extinguishment is integrated within the calculation process –

$$t_{ext} = 3.3 * \sqrt{A_{fire}} \qquad \textbf{\textit{Eq.12.4}}$$

Where:

t_{ext} time to extinguish the fire (mins)

A_{fire} Area of fire involvement (m2)

3.3 A coefficient based on the use of what is deemed adequate water (L/min/m^2)

The formula proposed for 'offensive' firefighting is therefore:

$$Fire_{off} = \frac{0.058 * q_k * \sqrt{A_f}}{K_w} \qquad \textbf{\textit{Eq.12.5}}$$

Where:

$Fire_{off}$ Required water flow-rate to achieve extinguishment (L/min)

k_W practical cooling efficiency of applied water (user's choice)

q_k fire load density for the compartment (MJ/m^2)

A_f Total internal floor area of undivided compartment (m^2)

Note: 'Offensive firefighting' here is defined as the process of extinguishing a building fire generally from interior positions.

139 Hadjisophocleous G.V. and *Richardson J.K.;* Water Flow Demands for Firefighting; Fire Technology, 41, 173–191, 2005

12.7 FIRE PROTECTION ENGINEER'S DESIGN GUIDANCE[140]

Prescriptive guidance in the UK

The existing guidance in the UK for providing firefighting water supplies to buildings and residential/industrial estates is as follows[141]:

	Occupancy	Minimum flow-rate
1	**Housing** to 2 Levels	480 L/min
	Housing above 2 levels	1200–2100 L/min
2	**Lorry/Coach Parks; Multi-Storey car parks or Service Stations**	1500 L/min
3	**Industrial** to 10,000 m^2 **Industrial** to 20,000 m^2 **Industrial** to 30,000 m^2 **Industrial** over 30,000 m^2	1200 L/min 2100 L/min 3000 L/min 4500 L/min
4	**Shopping; Offices; Recreation and Tourism**	1200–4500 L/min
5	**Education; Health; and Community Facilities**	
	Village halls	900 L/min
	Primary schools and single storey health centres	1200 L/min
	Secondary schools; colleges; large health & Community centres	2100 L/min

Table 12.5: UK Water/LGA/CFOA approved water provisions guidance

The above guidelines are only performance based as far as being based on research data provided in the 1950s-1970s, calculated on older traditional construction and fire loads. The existing prescriptive criteria in the UK for rising main and water storage provisions in tall buildings are as follows:

1	Fire mains should have a **<u>minimum</u>** 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 rising fire mains are to be provided where floor area exceeds 900m^2. (Building Regulations (Fire Safety) part B)
3	A **<u>minimum</u>** flow-rate from each wet riser of 1.67 L/min/m^2 (1500/900m^2) must be achievable (calculated from BS 9990:2015 and Building Regulations (Fire Safety) part B).
4	A maximum hose-lay distance (45 or 60m – depending on the existence of a firefighting shaft and sprinklers) is stipulated from each fire main, according to BS 9999:2008 and BS 9991:2011.

Continued overleaf.

140 A BS 7974 flow-rate design calculator tool, with added sprinkler compensations, can be downloaded from www.eurofirefighter.com

141 National guidance document on the provision of water for firefighting; UK Water & Local Government Association; with approval from the UK Chief Fire Officers Association. 2007

5	**Building Regulations (Fire Safety) part B; Section 15:** Where a building, which has a compartment of 280m² or more in area, is being erected more than 100m from an existing fire-hydrant, additional hydrants should be provided as follows; • **Buildings provided with fire mains** – hydrants should be provided within 90m of dry fire main inlets. • **Buildings not provided with fire mains** – hydrants should be provided within 90m of an entry point to the building and not more than 90m apart. • Each fire hydrant should be clearly indicated by a plate, affixed nearby in a conspicuous position, in accordance with BS 3251 Where no piped water supply is available, or there is insufficient pressure **and flow**** in the water main, or an alternative arrangement is proposed, the alternative source of supply should be provided in accordance with the following recommendations: • A charged static water tank of at least 45,000 litre capacity; or • A spring, river, canal or pond capable of providing or storing at least 45,000 litres of water at all times of the year, to which access, space and a hard standing are available for a pumping appliance; or • Any other means of providing a water supply for firefighting operations considered appropriate by the fire and rescue authority. **To achieve 'adequate' firefighting water (flow) a dry fire main is expected to achieve 7 bars at the highest outlet (50 metres) if pumped to 12 bars at the inlet, or 4 bars at the highest outlet if only pumped to 10 bars at the inlet (60 metres) (pre-2015 code). The quantity of water needed is not prescribed in the codes but an adequate amount for 2-3 firefighting hose-lines is considered to be between 1,000 and 1,500 L/min. The required flow-provision for residential premises may be less than that required for offices or commercial premises.
6	Pressure-reducing valves (wet-rising fire mains) 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 wet fire main is installed in a building, **the potential need for additional water storage and/or pumping capacity should be taken into account** (Building Regulations (Fire Safety) part B).

Table 12.6: Prescriptive requirements for rising fire mains and firefighting water storage in the UK

The final point in Table 12.6 (7) suggests that for each additional fire main above 900 m² 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 building regulation (1991 ADB) recommended two fire mains to every 2,000m² of floor area and an additional fire main was required after 2,000m² for each additional 1,500m², or part thereof. So, for a 3,500m² floor area above 60m in height, a flow provision of 1.29 L/min/m² was required. However, no consideration was given to occupancy type or compartment dimensions and the same provisions were applicable to small apartments, as well as large open-plan office floors.

Modern performance based codes in the UK

The GCU research has clearly established that the severity of building fires is dependent on several factors (listed below). It is further demonstrated that the quantity of firefighting water that may be deemed as 'adequate' may be effectively linked to the estimated ongoing heat release rate for any specific occupancy fire and can be presented on a gradient, 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). However, this finding is not reflected in current design codes.

It is demonstrated that **adequate** 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 combined with floor space ratios (A_v/A_f)
- An adequate water source being available in the first place

The actual flow-rates as used by firefighters to control over 5,000 serious building fires in the UK (2009-2012), in a wide range of occupancy types, is used to form equations for building and infrastructure design purposes. The formulae resulting from the Glasgow Caledonian University (GCU) research for non-sprinklered buildings are included in BS PD 7974:5:2014 and can be used to calculate the required flow (L/min), by applying flow-rate density per m^2 of floor area (L/min/m^2), for various occupancies based on the above six factors.

The following two charts demonstrate the flow-rate density outputs from the GCU research for building fires below 500m^2 in floor area (Fig.12.16) and large fires involving 500-10,000m^2 (Fig.12.17). It is this data from the firefighting flows used by the fire service to control and extinguish such building fires that was used to derive equations for performance based design purposes.

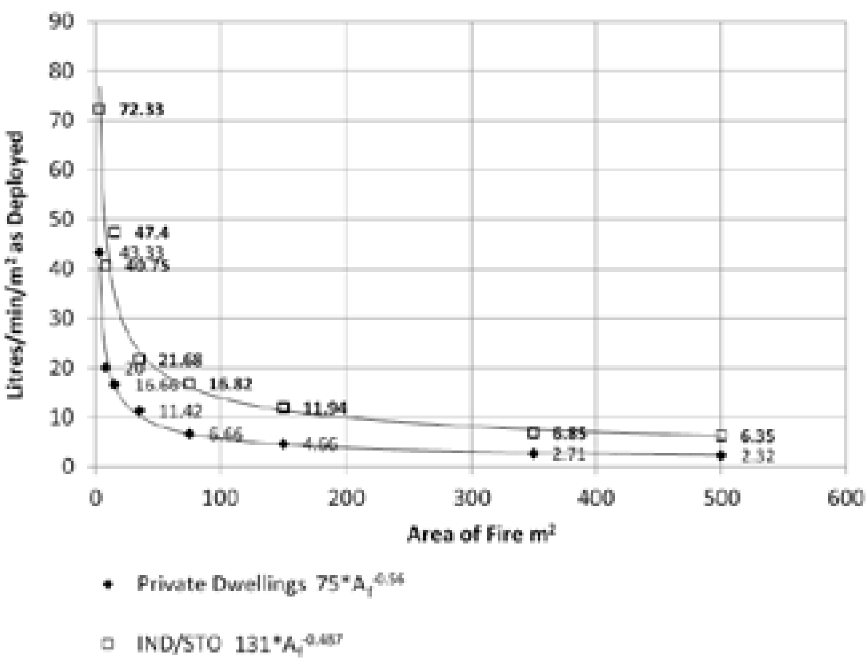


Figure 12.16: County/Metro fire fire-flow research of 5,401building Fires 2009-2012 showing deployed water flow-rates (L/min/m^2) for Private Dwellings and Industrial/Storage (INDO/STO) building fires less than 500m^2 fire damage.

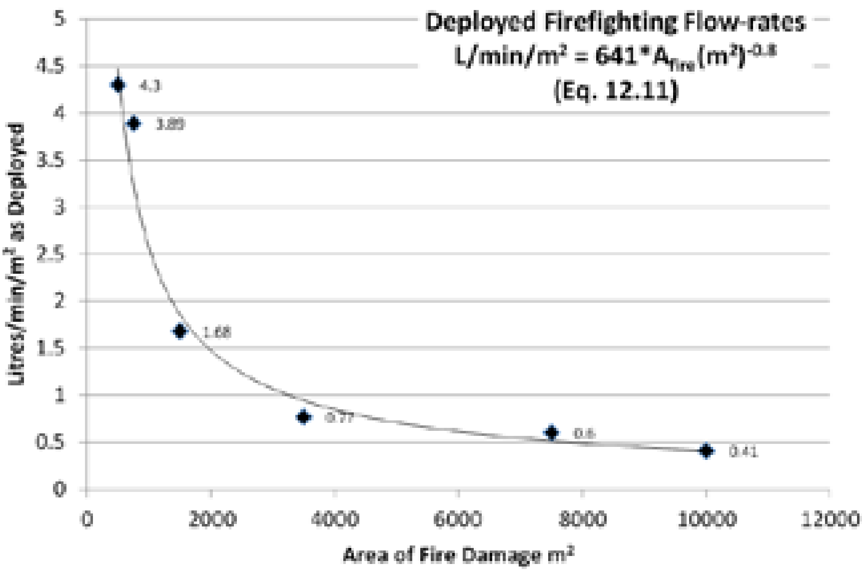


Figure 12.17: County/Metro building fire fire-flow research of 70 large Fires 2009-2012 in excess of 500m² (A_f) fire involvement.

As the fire engineer starts to apply the following formulae to projects, it soon becomes apparent that in some cases, greater amounts of water flow-rate (hence storage water) are calculated than prescriptive codes recommend. In other cases, it will be less. However, it's important to ensure that in any performance based design an adequate amount of firefighting water is provided to enable firefighters to contain fire spread. In some situations, this might require one hose-line using a flow-rate of just 500 L/min for 10 minutes, but in other situations it may take several hose-lines applying several tens of thousands of litres to achieve final extinguishment. Large office floors (for example) where sprinklers are not installed, or have failed, can lead to extended firefighting operations over several hours.

Ideally a fire should be handled by a single hose-line, with an additional safety hose-line in support, and this should be the objective in any design. As a rule of thumb, one hose-line has the suppressive capacity to handle anything up to a 20 MW fire. If the design fire, combined with the expected fire service response and deployment time (water applied to the fire), exceeds a 20 MW growth period then additional passive or active measures will be needed if the building is to be effectively protected. Clearly, early liaison with the local fire service is required for response and deployment analyses. Whilst no time-line can ever be guaranteed, the fire service should be able to provide data for expected response and arrival times for a varied percentage of circumstances.

The following equations for each occupancy group represent the starting point for designing firefighting water strategies:

The GCU – BS PD 7974:5:2014 Equations **12.6, and 12.7 (and 12.8 from Sardqvist's research)** below utilise occupancy type and floor area fire (m²) inputs whereas Equation **12.9** incorporates fire load density (MJ/m²), which can also be applied to high-stacked vertical fire loads (**Eq.12.10**).

For fires in dwellings (house, flats, maisonettes and apartments) – $F_{dwe} = 75 * A_{fire}^{0.44}$	**Eq. 12.6**
For fires in factories, industrial units and storage warehouses - $F_{ind} = 131 * A_{fire}^{0.51}$	**Eq.12.7**
For fires in public, office, commercial, schools, hospitals, hotels and smaller industrial buildings – $F_{other} = 61 * A_{fire}^{0.57}$ *(based on Sardqvist's 1998 research – see section 12.6)* 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} Floor area of fire involvement (m2)	**Eq. 12.8**
Or alternatively using the estimated fire load energy density (MJ/m²) for all building occupancies, from BS PD 7974:5:2014 - $F_{design} = 0.00741 * (q_k * A_f)^{0.666}$ Where: F_{design} design flow-rate for a fully involved fire compartment burning at maximum intensity (L/s) q_k fire load density for the compartment (MJ/m²) A_f total internal floor area of the fire resisting compartment (m²)	**Eq. 12.9**
Or for high-stacked fire loads (retail; industrial or storage etc) $F_{design} = 0.0074 \left((q_k * h) A_f \right)^{0.666}$ Where: **h** height of stacked storage (metres)	**Eq. 12.10**
For 1-2 storey, large floor area buildings, (infrastructure and estate planning) based on the GCU 70 large building fire research data 2009-2012 (fires were >500m² to 10,000m²) $F_{500\ design} = 641 * (A_f)^{-0.8)} = L/s$	**Eq.12.11**

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.

Obtaining Sprinkler compensations

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 3,000m^2 might consist of a 750m^2 central core and a 2,250m^2 open-plan office floorplate. With this design, there should be maximum hose runs from the centre of the core to the corners of the floor of around 40m. 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 the fire engineer should be looking for a compensatory coefficient to be included in the equations, acknowledging that although sprinklers are generally 97% effective, there is a 3% chance (or greater) they will not control a fire. At the heart of most sprinkler failures are management, maintenance and inappropriate system design issues. There are several methods open to the fire engineer to account for sprinklers in the calculation process that will reduce both firefighting water storage and supply provisions. (A firefighting *water flow-rate design* calculator spreadsheet can be downloaded from **www.eurofirefighter.com**).

Coefficients used in the calculations, that might be considered to compensate for approved fire suppression provisions, are available in:

- BS PD 7974
- NFPA 14
- Eurocode EN 1991-1-2 (Annex E)
- Points scale (GCU research proposal – below)

A BS PD 7974 probability model[142] has been applied to office buildings, retail premises and hotels in order to evaluate a suitable sprinkler coefficient, defined as the ratio between the design fire load densities for sprinklered and non-sprinklered compartments. The value of the coefficient, which depends on the distributions of fire load density for three occupancies, ranged from 0.53 to 0.68. These results showed that the fire resistance of sprinklered compartments of these occupancies might be around 60 percent of the resistance specified for non-sprinklered compartments, suggesting a possible 40 percent reduction coefficient for sprinkler provisions. The impact of sprinkler protection on fire resistance may be referenced in other ways[143]. In the case of BS EN 1991-1-2 and associated guidance in the form of BS PD 6688-1-2, the inclusion of fire load density in the calculation procedure may be reduced by 39%. This is on the proviso that life safety

142 British Standard PD 7974:7:2003, Application of fire safety engineering principles to the design of buildings, Probabilistic risk assessment

143 Hopkin. D; A Review of Fire Resistance Expectations for High-Rise UK Apartment Buildings; Fire Technology 2016

sprinklers (taken as 'additional measures to improve system reliability and availability' from 2015), in accordance with BS EN 12845, are provided. However, this may have the impact of distorting the resulting fire dynamics as the principle of using a straightforward post-flashover fire model, in practice, would not reach such severity should the sprinklers operate successfully.

Alternatively, more contemporary approaches seek to distinguish the structural reliability from the overall reliability of the fire resistance system through consideration of sprinkler reliability. The structural (or passive) reliability governing the fire resistance requirements of structural elements will depend upon the contribution (if any) from any proposed suppression systems of a given reliability.

As a further example of sprinkler compensatory coefficients, NFPA 14[144] may account for a reduced supply of firefighting water for sprinklered buildings by reducing the rising fire main (standpipe) and water storage requirements by 20 percent. Therefore, by adding a 0.8 coefficient to the calculations we can account for a sprinkler protected building by adapting NFPA guidance in the following way, in a 2,250m2 open-plan office floorplate:

$F_{other} = 61 * 2250^{0.57} * 0.8 =$ **3,973 *L/min*** *using* ***Eq.12.8***

$F_{design} = 0.00741 * (570 * 2250)^{0.666} * 0.8 =$ **4,159 *L/min*** *using* ***Eq.12.9***

In each case the practical design solution may be to provide two 150mm rising fire mains, each with at least two outlets per floor, providing a minimum total flow-rate of 4,000 L/min.

Two fire main outlets per floor assists the laying of an attack hose-line additional to a safety hose-line in support, from the same floor (preferably the fire floor, to reduce hose-lay distances and also to protect the stairs from smoke infiltration) – (confirm with local fire service procedures).

Using the above method for a sprinkler protected environment provides a minimum flow density of 1.8 L/min/m^2, which is considered a reasonable flow-rate for a sprinkler protected open-plan office floor plate. In comparison, a UK prescriptive design would require at least two 100mm fire mains providing 3,000 L/min in total, with or without sprinklers. This results in a flow density of 1.3 L/min/m^2, which is **below the critical flow rate** determined by GCU research.

The provision and effect of sprinklers to a reduction in the design value of the fire load [MJ/m^2] is also taken into account in Eurocode EN 1991-1-2 (Annex E) using factors considering different active firefighting measures. Two factors deal with sprinklers and take into account: automatic water extinguishing system (0.61) and independent water supplies (**0** = 1.0; **1** = 0.87; **2** = 0.7).

A simple but most effective system proposed within the GCU research incorporates a point scale where a building occupancy is risk-graded, based on the following factors:

144 National Fire Protection Association, NFPA 14:2013, Standard for the installation of standpipe and hose systems.

	• ***11-12 pts*** *Can achieve a 40% reduction in riser flow-rate and water storage provisions* • ***7-10 pts*** *achieves 30% reduction* • ***1-6 pts*** *achieves 20% reduction*	**Compensatory points**
A	Provision of 'additional measures' *(additional measures to improve sprinkler system reliability and availability' from BS-EN 12845 2015)*	**1**
B	The provision of zoned maintenance with additional live fire watch during system 'down' times	**1**
C	The provision of a BS 9999 level one management structure, meeting the requirements of PAS 7*	**1**
D	A structure designed mainly from concrete or steel framed construction (adds no additional fire loading in cases of intense fire spread) therefore less firefighting water would be required	**2**
E	Detailed analysis demonstrates an effective fire service intervention should occur (adequate water applied to the fire) prior to the fire reaching a stage beyond the control of a primary attack hose-line	**2**
F	A simultaneous or effectively phased evacuation strategy has been documented within the building fire safety plan	**1**
G	The potential for fire spreading to additional floor levels, above or below the floor of origin, has been countered by design (e.g.: combustible cladding, curtain walls or large window expanses avoided)	**2**
H	The existence of rigid cellular partitioning may slow the development of fire to a medium t-squared growth rate (no open-plan floor areas)	**2**

Figure 12.18: Glasgow Caledonian University Fire Engineering – sprinkler reduction points scale

As examples in using the GCU points scale, a building that is fitted with an ordinary hazard sprinkler system when only a light hazard system is required, or perhaps where additional measures to improve system reliability and availability are provided, will qualify for the two points under 'A'.

Taking the 2,250m^2 open-plan office floor-plate described above, by applying the GCU points scale effectively, a total of 11 points can achieve a 40 percent reduction in sprinkler flow, pump-set capacity and water storage, equating to the following:

$F_{other} = 61 * 2250^{0.57} * 0.6 =$ **2,980 *L/min*** *using* ***Eq.12.8***

$F_{design} = 0.00741 * (570 * 2250)^{0.666} * 0.6 =$ **3,120 *L/min*** *using* ***Eq.12.9***

So by using a performance based methodology that is founded upon the core principles of modern day fire attack data, we have still only matched a prescriptive flow-rate of just 1.3 L/min/m^2, but we have ensured in return, a very high standard of structural design and building management (PAS 7) as well as coordinating and gaining agreement with the fire service on their potential (a fair assumption but never a guarantee) to mount an early time-lined attack on the fire, based on standard response and deployment data for the area served.

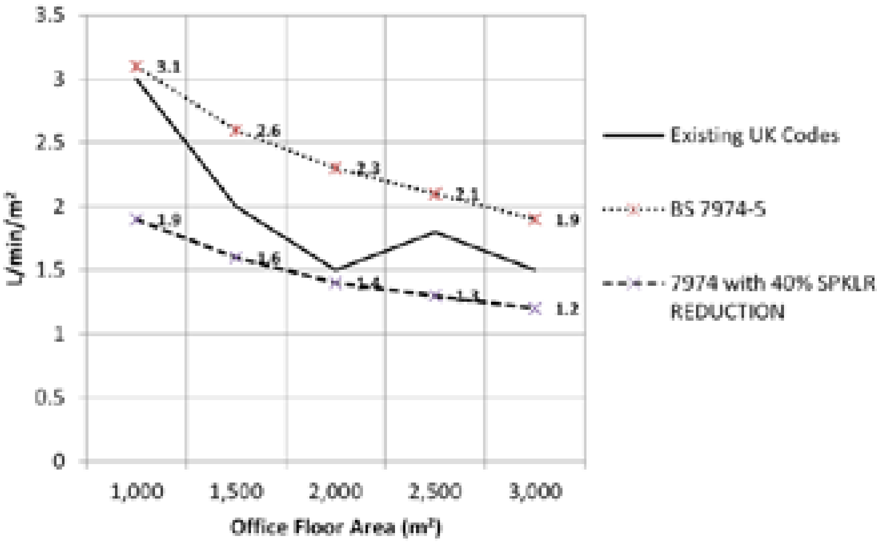


Figure 12.19: A comparison of flow-rate density provisions across occupied floor space, between prescriptive UK regulations and the performance based BS PD 7974:5:2014 (excluding core areas) where a 40% sprinkler reduction has been applied, in accordance with figure 12.17.

Equally, a 40% sprinkler coefficient might be used, based on the GCU points scale, when calculating fire protection for high-rise flats or 100m² apartments as follows:

$F_{dwe} = 75 * 100^{0.44} * 0.6 =$ **340 *L/min*** *using* ***Eq.12.6***

So, for a sprinkler protected 100m² apartment fire, with maximum hose distances within prescriptive limits from the fire main outlets, two hose-lines flowing 340 L/min (<u>one serves as a safety line, as needed in high-rise</u>) would be adequate. Therefore, the engineered flow provision is rounded to 700 L/min, with a much-reduced water storage and pump set requirement in buildings >30m in height, compared to a code compliant provision. Again though, we have traded needed firefighting water flow-rate and storage provisions for sprinklers, coupled with reliable construction under fire, 'PAS 7' management levels and effective firefighting access, systems and facilities maintenance, and alarm/evacuation arrangements (possibly public address voice alarms) that have all been considered, even if it's just the fire floor and local zones above and below that are initially evacuated.

Isolated Buildings – no immediate Water Supply

In some rural situations, there is coded guidance for establishing water storage provisions where the nearest water supply is several miles away from a building. In the UK building regulations (ADB) the provision of a large static tank of at least 45,000 litre capacity is sometimes used as a reference point. This enables a 45-minute supply at 1,000 L/min firefighting water that may need to be topped up from an alternate source. However,

* PAS 7: 2013 Fire risk management system, Specification, British Standards Institute

taking this need for an isolated water supply, it makes sense to calculate a needed flow-rate density per m^2 of floor area, also taking sprinkler compensatory coefficients into account. Therefore, based on 7974-5 flow-rate density guidance, a two-storey house isolated from a firefighting water supply by some great distance could be provided with a calculated water storage provision as follows –

Two storey non-sprinklered house with a total (2-floors) floor plate of $600m^2$ requires the following storage water for firefighting:

F_{dwe} = 75 * 600 $^{0.44}$ * = **1,252 *L/min*** *using* ***Eq.12.6***

Then, 1,252 L/min x 30-minutes supply = 37,560 Litres
1,252 L/min x 45-minutes supply = 56,340 Litres

With sprinklers installed, the same water supply serving sprinklers could be combined to provide 750 L/min of firefighting water (22,500 Litres for 30-minutes supply at 40% compensatory reduction for sprinklers). A smaller house of just $300m^2$ total floor space across two floors would require a far lesser firefighting water provision.

Note: Based on UK Water guidance 2007, a flow of only 480 L/min is required, totalling 21,600 L/min for a 45-minute supply. Such a supply may be adequate for a single firefighting jet only, but would not enable an additional safety jet to be deployed to optimise firefighter safety.

12.8 FIREFIGHTING WATER CALCULATOR TOOL (BASED ON BS 7974-5:2014)

A firefighting water calculator spreadsheet tool, based on the BS 7974-5:2014 (Fire Service Intervention) guidance has been developed. The tool offers the user the means to compensate the design if sprinklers are fitted and the 8 points on the GCU scale (Fig.12.18) have been addressed. This tool can be downloaded for free from **www.eurofirefighter.com**.

12.9 TRAVELLING FIRES

A review of fires in large open-plan compartments (typically with floorplates greater than 200 m^2) reveals that in general, these fires do not conform to normal *flashover* fire development where fire involves the entire enclosure at one time. Instead, these fires tend to move across floor plates, reaching peak levels of heat release across a limited or zoned area at any one time. These fires have been labelled *travelling fires* and in some texts this process of fire development has been referred to as *progressive burning*.

Fire spreading across a large open-plan office floor is typical of this type of behaviour where 'fast and even ultra-fast ***t-squared***' growth rates during the initial few minutes may well be reached, with average fire spread rates in excess of $22m^2$/min. It may appear that the entire floorplate is burning; however, the fire will likely be at different levels of intensity across the floor space. 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 distant far field areas burning into the decay stages.

A fire involving an open-plan 1,400 m^2 office floor plate located around a central core is more likely to demonstrate peak heat release rates across three zones of $470m^2$ or four zones of $353m^2$, 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. In terms of meeting an adequate firefighting water provision the concept of a 'travelling fire' in large enclosures should be looked at primarily using a growing fire analysis. If fire service intervention is unlikely to control the fire at the point the primary hose-line is deployed then additional active or passive fire protection features, or the effective siting of additional firefighting shafts with 150mm fire mains to support multiple secondary hose-line deployments at the fire floor, should be considered and discussed with the fire service at the Qualitative Design Review (QDR) stage.

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 LAFD fire chiefs and firefighters who fought the fire.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 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 temporarily 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 central core that contained lifts, stairs and service shafts. The office space surrounding the core measured 188 metres by 7.5 metres, totalling 1,410 square metres. The 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 minutes 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 square metres of floor space per minute. The fire has been analysed here 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 20-25% A_v/A_f vent opening to 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.

Even though earlier attempts were made, Los Angeles firefighters were unable to deploy adequate water until 34 minutes 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

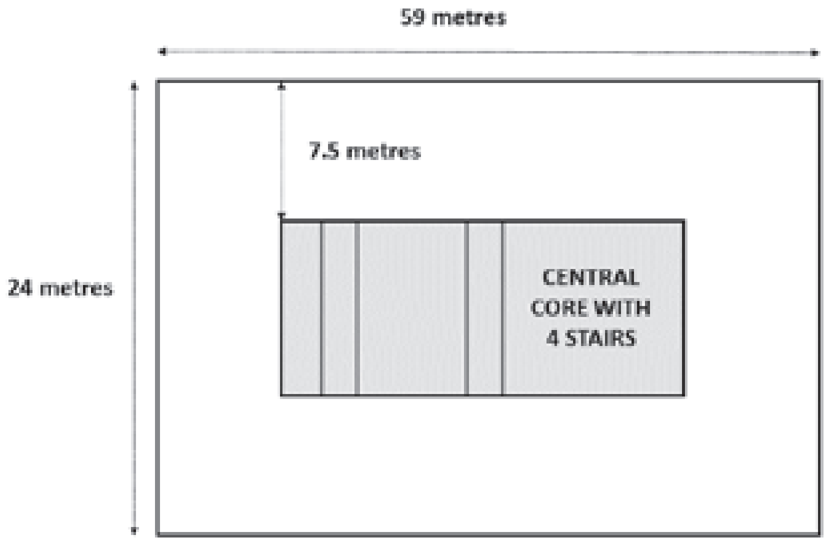


Figure 12.20: Plan of the 12th floor at the First Interstate Bank 1988

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 minutes 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.

Los Angeles Fire Department Operations

At 2237, the Fire Department received three separate 9ll calls from people outside of the First Interstate building reporting a fire on the upper floors[145]. At 2238, a Category 'B' assignment was dispatched consisting of Task Forces 9 and 10, Engine 3, Squad 4, and Battalion 1 -- a total of 30 personnel. (A Task Force in Los Angeles consists of 10 personnel operating two pumpers and one ladder truck.) The first report of the fire from inside the building was received at 2241, as the first due companies were arriving at the scene. While responding, Battalion 1 had observed and reported a large 'loom-up' in the general area of the building. As he arrived on the scene, the Battalion Chief observed the entire east side and three-fourths of the south side of the 12th floor fully involved with fire. Battalion Chief Don Cate immediately called for five additional Task Forces, five Engine companies, and five Battalion Chiefs. This was followed quickly by a request for an additional five Task Forces, five Engine companies and five Battalion Chiefs, providing a total response of over 200 personnel within five minutes of the first alarm. Two Fire Department helicopters were also dispatched. The High-rise Incident Command System was initiated with companies assigned to fire attack and to logistics and support functions from the outset.

In accordance with Los Angeles City Fire Department policy, elevators were not used and all personnel climbed the stairs to the fire area. The first companies to reach the fire

145 Extract from United States Fire Administration (USFA) report 1988

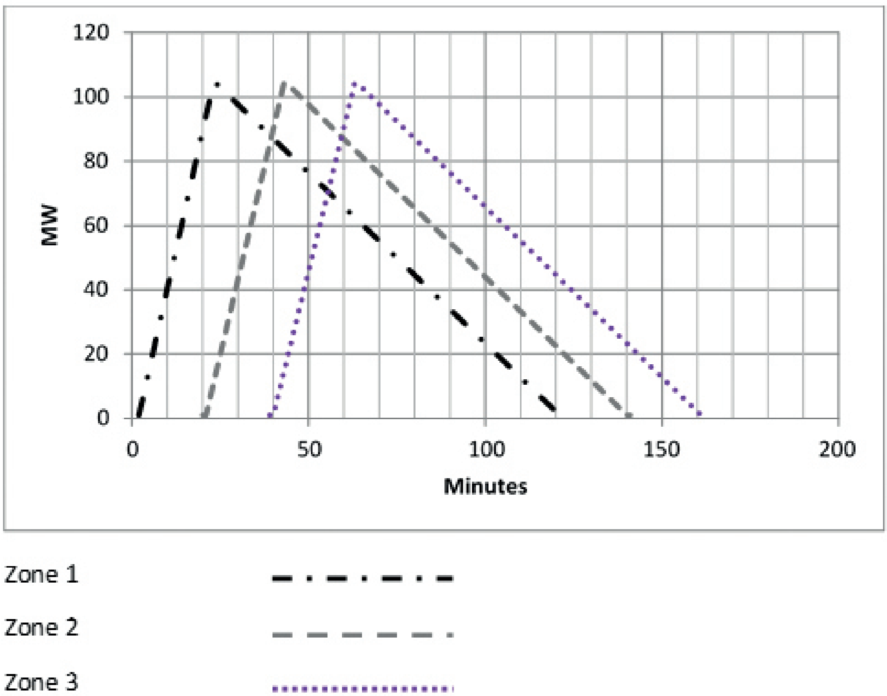
floor found smoke entering all four stair-shafts from around the exit doors. Hose-lines were connected to the standpipe risers and the initial attack began at approximately 2310. Due to the magnitude of the fire on the 12th floor, attack was initiated from all four stairways. The crews had great difficulty advancing lines through the doors and onto the floor. As the doors were opened, heat and smoke pushed into the stairways and rose rapidly to the upper levels of the building.

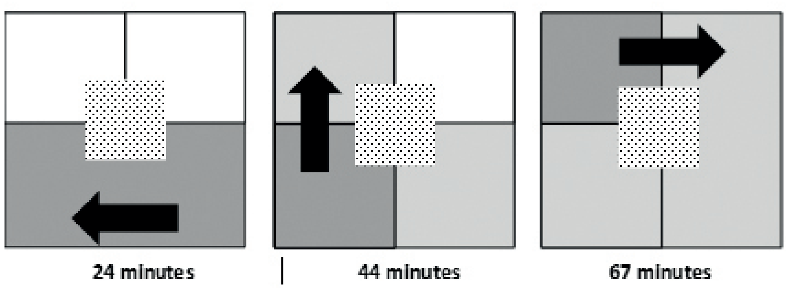
First Interstate Bank Fire 12th Floor analysis	3 Zone Fire	4 Zone Fire	Entire 12th Floor
Floor Area (m^2)	470	353	1410
Heat of combustion (MJ/kg)	20	20	20
Fire load energy density MJ/m^2	570	570	570
Estimated fire load (kg)	13,253	10,046	40,185
Fire growth rate	Fast	Fast	Fast
Ventilation or fuel controlled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

Table 12.7 Travelling fire analysis at the First Interstate Bank Fire in 1988 (Firesys)

'Firesys' is a detailed suite of fire modelling spreadsheets, developed by New Zealand structural and fire engineer Cliff Barnett. In 2004 the author combined his previous research with Barnett's work, providing flow-rate input to Firesys model 8-E, using data outputs from the 100 fire study in London (1989). The foundation of the Firesys model is based on the BFD Curve, an alternative "natural" fire curve that, according to Barnett, fits the results of large scale fire tests closer than any previously known fire modelling methods (2007) including Eurocode parametric curves.

A Firesys spreadsheet calculator can be downloaded from **www.eurofirefighter.com**





Figures 12.21 & 12.22 – Three Zone model (Interstate Bank fire)

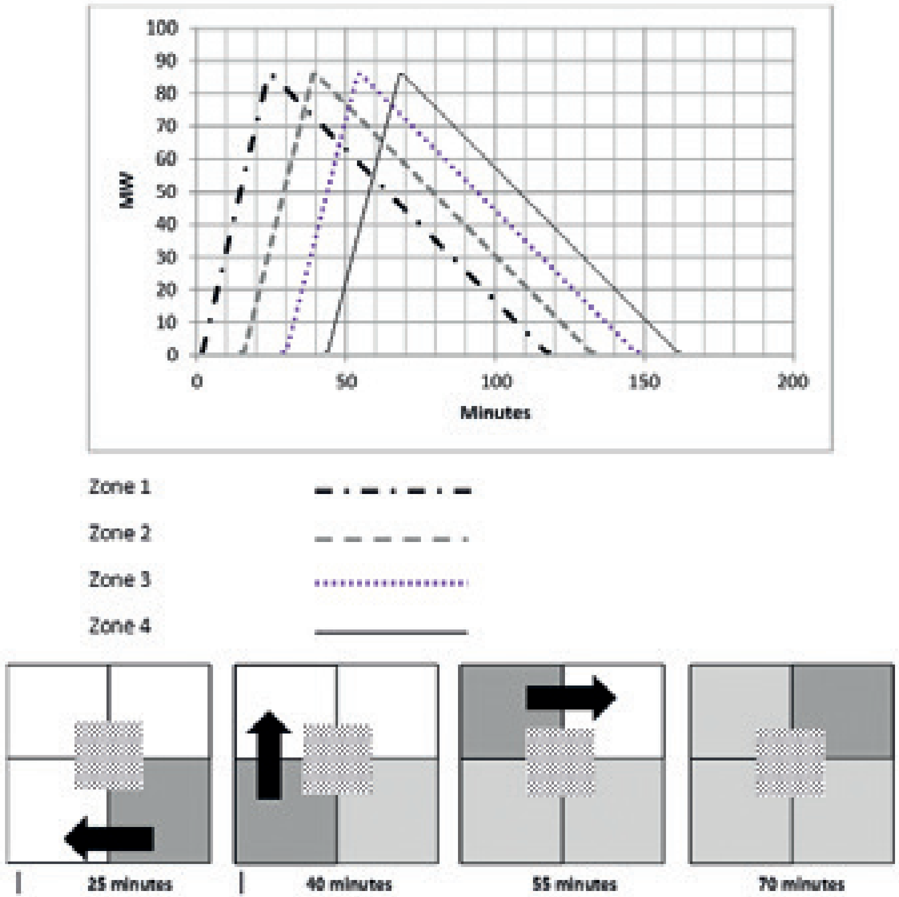


Figure 12.23: Four-zone model of heat-release rates on the 12th floor at the First Interstate Bank fire 1988 / Figure 12.24 – Four Zone model (Interstate Bank fire)

First Interstate Bank Fire (1,410m^2 12th Floor) (Fuel control Fire)		
Mass of fuel	40,185	kg
Calorific value used	20	MJ/kg
Fire Load Density	570	MJ/m^2
Energy contained in fuel	803,700	MJ
Growth factor (fast fire)	150	s
Peak Heat Release Rate (PHRR)	217.8	MW Q_{max}
Time to reach PHRR (growth phase)	36.9	mins
Energy released over time	160,736	MJ
Decay factor	600	secs
Time to end of decay phase	147.6	mins
Energy released in time	642,959	MJ
Total duration of burning	<185	min
Heating efficiency	0.50	k_F
Cooling efficiency	0.63**	k_W
Firefighting water flow-rate required L/s	66 (3,960 L/min)	L/s

Table 12.8: The design fire and flow-rate calculations used in 'Firesys' for the Interstate Bank fire:

*Note: A 63% efficiency factor** is applied due to a fuel-controlled fire mostly likely extinguished in the decay phase (based on data from 100 large fires) – this is not a design fire calculation.*

Calculating Adequate Water for the Interstate Bank Fire

The design flow-rate for the 1,410-square metre open-plan office floor space at the building can be calculated using Eq.12.8 or Eq.12.9 as follows:

$F_{design} = 0.00741 * (570 * 1410)^{0.666}$ = **3,808 *L/min*** *using* ***Eq.12.9***

$F_{other} = 61 * 1410^{0.57}$ = **3,805 *L/min*** *using* ***Eq.12.8***

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

<u>3 Zone model:</u>

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

$$F = \frac{0.5 * 104}{0.5 * 2.6}$$ = **2,400 *L/min*** *using* ***Eq.12.1***

Added to this will be a requirement to deal with adjacent zones, mostly during decay stage burning, where 2 l/min/m² may be generically applied as follows –

Two additional zones of 465m² totalling a potential 930m² of decay stage burning leading to an additional requirement of 930 x 2 = **1,860 L/min**

2,400 + 1,860 = **4,260 L/min**

Alternatively, where additional zonal floor space calculated as *decay stage burning* is greater than 1,500m² then the calculation given in figure 12.16 (chart) may be used in addition to Eq.12.1 requirements.

<u>4 Zone model:</u>

353m² fire area at 86MW Q_{max}

$$F = \frac{\mathbf{0.5 * 86}}{\mathbf{0.5 * 2.6}} = \mathbf{1{,}984}\ \textbf{\textit{L/min}}\ \textit{using}\ \textbf{\textit{Eq.12.1}}$$

Added to this will be a requirement to deal with adjacent zones, mostly during decay stage burning, where 2 L/min/m² may be generically applied as follows –

Three additional zones of 353m² totalling a potential 1,059m² of decay stage burning leading to an additional requirement of 1059 x 2 = **2,118 L/min**

1,984 + 2,118 = **4,102 L/min**

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 totalling 4,000 L/min (2.83 L/min/m²) were deployed internally on the 12th floor (totalling 9,000 L/min to all fire involved floors from four 150mm fire main stand-pipes). To ensure this water continued to flow, firefighters were relieved at approximately 15 minute intervals on each hose-line. The staffing and resource demand was extremely high.

The fire extended at a rate estimated at 45 minutes per floor and burned intensely for approximately 90 minutes on each level before entering the decay stages of burning. This resulted in two floors being heavily involved at any point during the fire. The upward extension was stopped at the 16th floor level, after completely destroying four and one-half floors of the building.

Using the following equation, the time needed to effectively extinguish a fully involved fire on floor 12 can be estimated as follows:

$$t_{ext} = 3.3 * \sqrt{1{,}410} = \mathbf{124}\ \textbf{\textit{min}}\ \textit{using}\ \textbf{\textit{Eq.12.4}}$$

THE FIRE	**Interstate Bank LA 1988 – 4 Zone Fire**
Q_{max} PHRR (MW) also (MJ/s)	86.4 MW as 4-zone travelling fire
PHRR at 50% Comb Efficient k_F	43.2 MW
Duration of Steady State Fire	11.6 min
Mass Loss (kg) at Steady State	2727 kg
Maximum rate of burn kg/s	3.9 kg/s average (peak at 4.3 kg/s accounted for)
Maximum rate of burn kg/min	258 kg/min
Energy Release at Q_{max} MJ	54733 MJ
Energy Release at Q_{max} MJ/s	86.4 MJ/s
Energy Release at Q_{max} MJ/min	5184 MJ/min
Energy Release at 50% Comb Efficient k_F	2592 MJ/min at 1.5 MW
THE WATER	
ADEQUATE WATER **(Barnett) 0.38 L/s/MW** **(Grimwood) 0.40 L/s/MW** **RASBASH/GRIMWOOD** *Note: According to several studies, extinguishing efficiency (Fig.12.8) is estimated to be between - 32-35% directly at the fuel base and 15-18% when water is applied into the flaming reaction zone.* *The remaining 50% of water applied is generally seen to 'run-off' with minor cooling effects.*	0.38 x 86.4 MW = 32.8 L/s At Q_{max} = 1968 L/min 0.36 x 3.6 x (1/0.3) x 32.8 x 0.18% = 25.48 MW 0.64 x 2.6 x 32.8 x 0.32% = 17.46 MW **Total** = **43 MW** Q_s = 43 MW / 0.5 k_F = 86 MW per 32.8 L/s 86 MW / 32.8 L/s = 2.62 MW/L/s 32.8 L/s x 2.62 MW = 86 MW Q_{max} 32.8 / 86 = 0.38 L/s/MW
THE HEAT EXTRACTION	
Reaction Zone (RZ) @ 50% Combustion efficiency Gaseous Phase	43 MW 43 MJ/s 2580 MJ/min
Water reaching RZ	36% of 1968 L/min = 708 L/min (12 L/s)
Water need in Suppression of RZ	2580 MJ to be extracted Therefore at least 717 L/min is needed; (2580 MJ / 3.6 MJ/kg); The remaining 64% of applied water (1,259 L/min) is used to cool the fuel base – an application rate of around 3.6 L/min per m2 of floor surface coverage is needed.

Table 12.9 - Summary of the Interstate Bank firefighting water flow requirements

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

What does this mean to the Firefighter?

As a fire begins to spread across open-plan floor space with low ceilings, such as in an office building, the speed of deployment to get initial water on the fire must be rapid if the fire is to be controlled. Past experience has shown us that such fires spread at an average rate of around 22 square metres every minute in these buildings and once a fire reaches one metre in height, the suppressive capacity of a hose-line is likely to be surpassed within the next 10 minutes (500 L/min) or 13 minutes (750 L/min) or 15 minutes (1,000 L/min), as the fire takes hold on the floorplate and develops into its fast growth curve.

Where there are high ceilings (storage warehouse), such rapid fire spread will depend on the vertical fire load and the distances between stacks of goods, where un-sprinklered or unvented fire development may be equally dramatic as burning brands quickly spread fire around and internal racking collapse becomes the primary hazard. In these instances, the smoke layer may drop rapidly upon firefighters, sending them into darkness and increasing their vulnerability to hidden fire spread in the overhead. Definitely something that should be anticipated and a planned evacuation from the structure may need to be made ahead of any such conditions occurring.

12.10 THE IMPACT OF INADEQUATE FIRE MAIN CAPACITY ON FIRE SERVICE INTERVENTION

Some evidence based analysis should be applied to the predicted point in time at which the effectiveness of fire service intervention begins to fail and where additional active or passive fire protection measures might be considered as part of the overall fire strategy for a building. Depending on the design for any particular building objectives (including life safety, business resilience and environmental impact), the most extreme fire may be expected to be one that remains within the largest single fire resisting compartment. Where fixed fire suppression exists, the largest fire is estimated according to the design capabilities of such systems. It is this basis upon which most methodologies relating to firefighting water provisions and needed flow-rate are founded, although consideration should be given to the reliability, probability and consequences of such systems or barriers failing to meet design needs effectively when required. Where a fire spreads beyond the largest fire resisting compartment upon which firefighting water design calculations are based (GCU statistics suggest 47% of ‘working fires’ will do this), building design objectives are generally seen to have failed and the structural elements themselves as well as adjacent exposures may be at risk. In the case of some low-rise buildings this may be considered a reasonable and acceptable worst case scenario.

There are targeted time frames on how quickly and how effectively the fire service are able to apply water (or other suppressive agents) into a fire involved area before the elements of structure are compromised or before the fire spreads unsafely and unplanned, beyond the fire resisting compartment of origin. At some stage the fire will move into the decay phase of fire development where the maximum rate of heat (energy) release (Q_{max}) is surpassed and therefore a lesser amount of water becomes necessary to control the fire. The general trend suggests that effective fire service intervention operations began the transition into ‘defensive mode’ as primary flow rates into large floorplates fell below

3.75 L/s/m^2 and/or the fire involvement exceeded 600m^2 in floor area. It should be re-emphasised here that flow-rates below 4 L/s/m^2 are seen to create an element of added thermal exposure to firefighters and therefore their working times on the floorplate are decreased and additional staffing and resources are needed in support, as fire floor relief times are reduced.

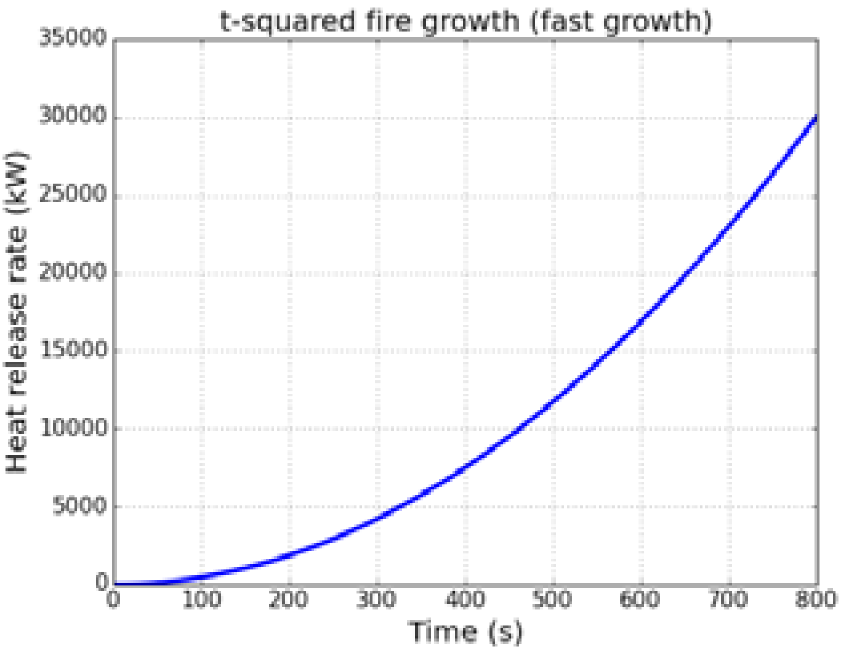


Figure 12.25: A t-squared fire growth curve demonstrating a 'fast' growth rate.

At this juncture, the ability of any specific fire service intervention to be able to contain, control and extinguish a large developing fire will depend on a 'window of opportunity' related to the fire size and speed in deploying 'adequate' water; the staffing resources and equipment available in support of maintaining an attack on the fire, and viable access to the burning fire load. Also, consider the subjective statement of US fire chief Bill Peterson that there is likely to be a 50 percent failure rate in interior fire service control once fire development has surpassed 86m^2 in floor area on first deployment into large floor space. Similarly, 'the rule of thumb' guidance that a primary attack hose-line flowing 500 L/min offers a suppressive capability of up to 20 MW of heat release should be considered. These two practical firefighting estimates appear very close in their recommendations.

As large fires develop beyond the initial control of fire service intervention, a lesser amount of water is then required once the fire burns into decay stages and this will be a time dependent turning point. The example of the Interstate Bank fire demonstrates adequate water was achieved at 2.8 L/min/m^2 just before the stability of the structural frame was threatened. The calculated design requirements for adequate water in this building (without sprinklers functioning) ranged from 2.7 to 3.0 L/min/m^2. To achieve these firefighting water flow-rates the First Interstate Bank had four 150mm wet risers serving the 1,400m^2 floor plates, with two 2,800 L/min pumps and water storage that would allow 81 minutes of continuous firefighting at a 4,000 L/min flow-rate. In comparison, the current UK regulatory guidance for rising mains in this building would recommend just 2.1 L/min/m^2 flow coverage from two 100mm rising mains. However, if maximum hose-run distances conformed to 45-60m from the central core, then the UK flow requirement could be halved to 1.0 L/min/m^2 (single 100mm main) which would be grossly inadequate to sustain an extended firefighting operation on a single fire floor.

A good example of an engineered rising main strategy can be seen in Singapore, where the vast majority of high-rise office buildings provide adequate firefighting water with a minimum flow in the first riser in use of 2,280 L/min (2x300gpm (US) hose-lines) and 1,140 L/min in subsequent risers brought into operation, providing a minimum flow coverage of 2.45 L/min/m^2 on a 1,400m^2 floor plate. These flows are achieved via 150mm wet risers with two floor outlets per rising main in all office buildings over 45m in height.

12.11 THEN THERE WERE 249 MORE FIRES … 2015–16 (POST-SCRIPT)

As a post-script to his PhD research, the author undertook further analysis of an additional 249 'working' building fires that occurred in Kent, UK from April 2015 to April 2016. In order to ensure a comparable analysis, again all fires were considered as 'working' fires with derelict building fires in both sets of data excluded. A new response model had been introduced across the service's 56 fire stations, covering an area of 3,544 km^2 with a Population Density of 413 people/km^2. This new fire service response and deployment model was the outcome of a two-year service delivery capability review combined with financial funding restrictions following UK government requirements to optimise the public service delivery. It led to changes in response, attendance times, training, equipment, firefighting tactics and intervention strategies. The ultimate optimal performance objectives were to reduce life losses through fire, and from this particular research perspective the amount of fire damage resulting from building fires, or the ability to contain fires to smaller areas, is considered as a logical method in measuring service delivery and performance at building fires (**property protection**).

In the three-year period 2009-2012 in Kent there were 4,430 building fires that resulted in 1,152 working fires and from 2015-2016 (after the changes to the response and deployment model had been made) there were 291 fires, that fell into the category of *working fires in occupied buildings*. The new equipment being introduced on the fire-ground included –

- A wider use of Positive Pressure Ventilation (PPV) as an attack tool (PPA)
- The introduction of 22mm high pressure hose-reels flowing 200-250 L/min as a first-strike tool compared with 19mm reels (110 L/min) that were most commonly utilised in the 2009-12 research period
- The provision of 22mm diameter smooth-bore nozzles across the 56 stations (complementing the automatic nozzles already provisioned) to deal with high-rise fires above the 10th level and also rapidly developing fires elsewhere with a higher flow-rate being achievable at lower nozzle pressures
- Portable attack monitors on all fire engines, again to provide greater flow-rates where needed
- Larger diameter attack hose-lines such as 51mm replacing 45mm attack hose
- 90mm supply hose-lines replacing some 65mm for use with portable monitors or

as hydrant supply hose where one 90mm line can equal the flow of two 65mm lines, freeing up staffing on the fire-ground to initiate fire attack more quickly;
- 'Fog-spike' (fog-nail) water-fog insertion nozzles, issued to all fire engines, supported by five COBRA units, used where fire is contained to small compartments or is spreading through structural voids and attic spaces making access difficult.

The changing dynamics of our building fire environment warranted some updating of the fire response model and these changes have clearly been justified when comparing the fire data both from before and after changes were made (Figs. 12.26 and 12.27) – an increased target flow-rate and tackling roof-space and void fires more effectively being central to the changes.

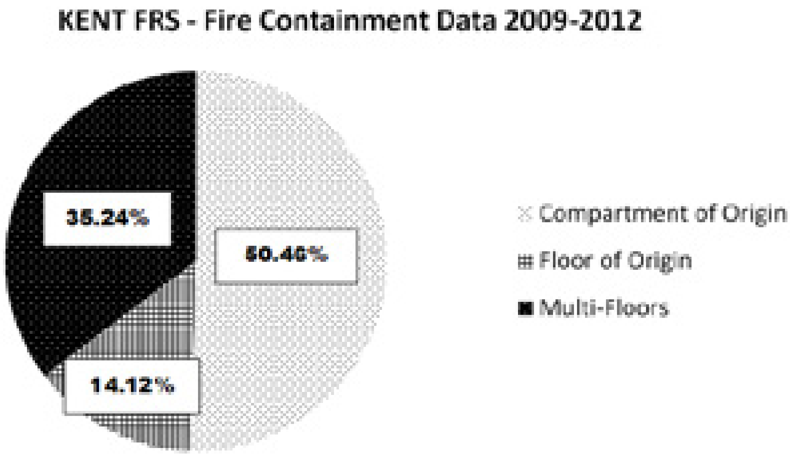


Figure 12.26: The data from the Kent (County) fires in 2009-2012

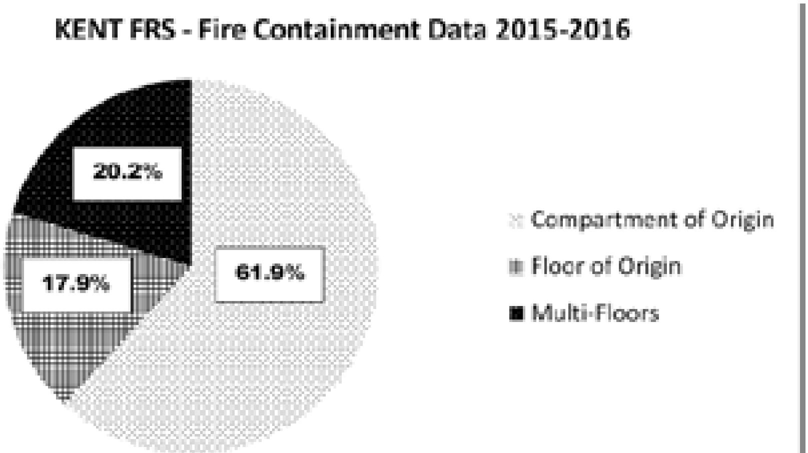


Figure 12.27: The data from the Kent (County) fires in 2015-16

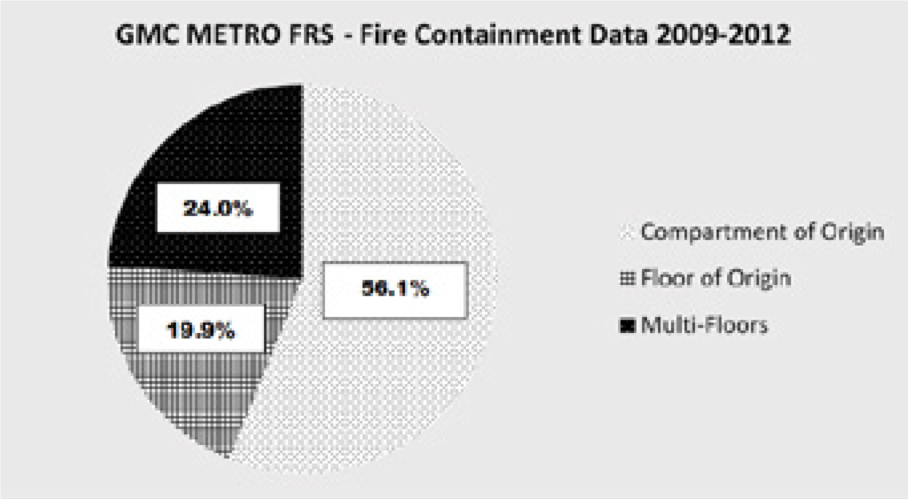


Figure 12.28: The data from the GMC (Metro) fires in 2009-2012

High Pressure (HP) versus Low Pressure main Hose-line attack

HP is certainly nothing new, using small diameter rubber hose-tubing (19mm-25mm diameter bore) to discharge small amounts of water (100-300 L/min) at high pressure (around 30-50 bar at the pump) into the fire can create some impressive knockdowns. Similarly, fog insertion tools such as COBRA (UHP) can provide very finely divided water-fog streams. The firefighting method can be traced back as far as the Royer/Nelson IOWA and Lloyd Layman research in the 1940–50s. It is a strategy that has been well used by London Fire Brigade and throughout Europe for several decades with some great success.

2 x 20m x 22mm hose-reel (40m total length)			
20 bar @ Pump	25 bar @ Pump	30 bar @ Pump	35 bar @ Pump
170 L/min	250 L/min	270 L/min	300 L/min

*Table 12.10: Even higher flow-rates are achievable by reducing the total length of 22mm hose-reels to just 40 metres, although this length **does not integrate with building regulation design specifications** for firefighting access to apartment blocks (45m from fire appliance/engine to furthest apartment).*

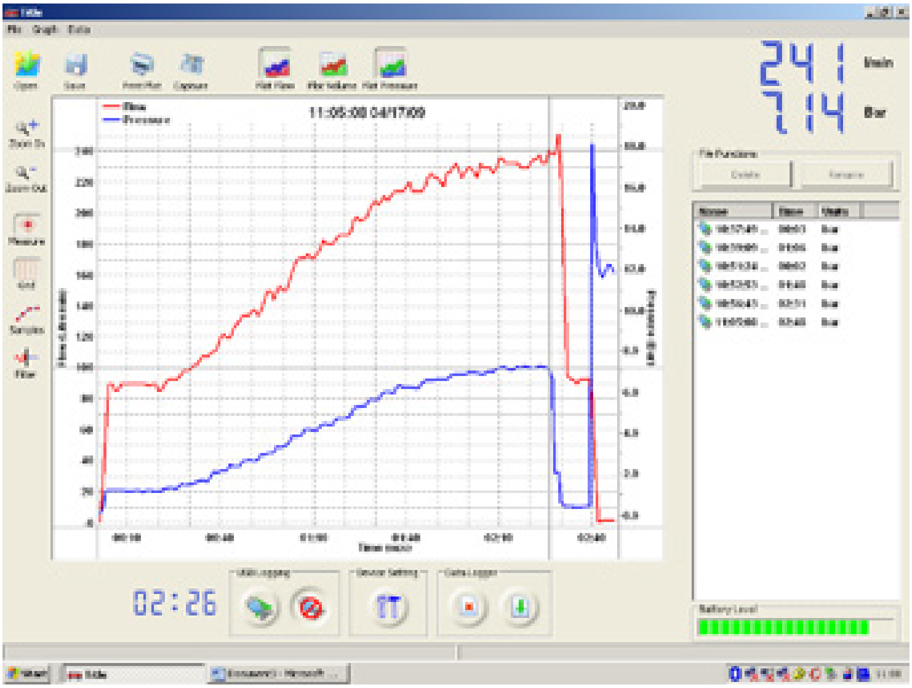


Figure 12.29: To achieve 7 bar and 240 L/min at the nozzle of a 55-metre run of 22mm high-pressure hose-reel you may need to pump to >40 bar at the pump (3,200 RPM) – a 100% improvement in flow compared to a 19mm hose-reel.

What does this mean to the Firefighter?

Advantages of High-pressure

- Very quick to deploy water on fire
- Firefighting water tank lasts longer (lower flow than main-line hose)
- Less staffing required
- Less reliance on hydrant support
- Can easily be deployed to 4-5th storeys by rope line, hauled aloft
- A 120 L/min HP hose-line may be equal in gas-phase suppressive capacity to a 350 L/min low-pressure line (three times more effective)
- Great tool to access fires in voids
- 76% of 5,401 working UK building fires** were dealt with using 19mm HP hose-reels

Disadvantages of High-pressure

- Crews can become over-confident in HP's suppressive ability
- The low flows have distinct suppressive limits in the fuel-phase
- Firefighters can get into trouble quickly if caught by sudden fire spread
- In timber frame properties, the fire load may be too much for UHP to handle
- May increase levels of thermal exposure experienced by firefighters (some fires take longer to extinguish)

*** Glasgow Caledonian University (authors) research 2015 (described in this chapter)*

The use of HP pumps and small diameter hose-line may increase stream velocity, reduce water droplet size and can increase suppressive capacity in the gas-phase

Continued overleaf.

by up to 3 times, when compared to low pressure streams at the same flow-rate. However, where the fire growth rate is rapid, or where the fire load is heavy (or the structure becomes the fire load), the low flow-rate may then expose firefighters to dangerous levels of thermal exposure for an increased duration. However, the innovative use of UHP COBRA/PYROLANCE or FOGNAIL/FOGSPIKE tools (piercing nozzles) applied from external positions is increasing cross Europe.

12.12 19mm DIAMETER HOSE-REELS

The use of 120 L/min 19mm hose-reels in the UK is finally being acknowledged by many as an outdated and potentially dangerous practice when matched against the higher fire loads and the more intense and faster compartment fire spread being seen today. The author has been campaigning now for nearly two decades for European fire services to recognise that the time for change has come. His work with London Fire Brigade in 2006 has finally resulted in the introduction of 22mm high-pressure reels flowing up to 250 L/min and carrying near equal suppressive capability as 45mm low-pressure hose-lines. Similarly, Kent Fire and Rescue Service, Greater Manchester FRS and several other fire services have implemented the same transition to 22mm reels. We have seen recent fires in London, Warwickshire and Manchester where firefighters have lost their lives after 19mm reels had been deployed on arrival into commercial and industrial premises for periods in excess of 30 minutes before higher flow hose-lines were decided on. The question needs to be asked, is it viable to deploy eight firefighters with four hose-reels into a fire or is this a misuse of resources. Are four low-flow tactical vantage points equal to one or two higher flow options? Is a total of 500 L/min applied from four locations better than a total of 1300 L/min applied from two vantage points? Should we be looking to deploy greater numbers of firefighters to manhandle larger hose-lines earlier on in commercial buildings to achieve better effect?

These considerations are of course dependent on various strategic factors and may vary according to the type of fire or occupancy profile. Greater Manchester FRS achieved good effect in the flow-rate research (County v Metro) above in flowing two or more hose-reels during the initial stages at many of their fires but most of these were in domestic properties. However, I am a strong believer that we should deal with 'working fires' involving commercial and industrial fire loads from the outset, using minimum flows of 500-700 L/min per hose-line. Such hose-lines demand an appropriate staffing deployment of 2-4 per line. At any stage that firefighters are advancing hose-lines into such occupancies, safety hose-lines of *equal flow* or *suppressive capability* are also a primary need at an early stage.

The Reaction Zone – Cooling Mechanisms and Heat Extraction

- Cooling the fuel surface, which reduces the pyrolysis rate and so the rate of fuel supply to the flaming reaction zone, thus reducing the heat release rate and the radiative feedback from the flame to the fuel surface.
- Cooling the flame zone directly, which disrupts the chemical reactions responsible for combustion. Some portion of the heat of reaction is abstracted in heating and evaporating the liquid water; therefore, less thermal energy is available in the vicinity of the reaction zone.

	Room Fire	CCAB Chicago Office	Interstate Bank**
HEAT PROFILE			
Floor Area m²	12 m²	244 m²	353 m² (Zone 1)
Fire Load Mass kg	520 kg	6,977 kg	10,046 kg
MJ/kg Calorific Value Heat of Combustion	18 MJ/kg	20 MJ/kg	20 MJ/kg
FLED MJ/m²	780 MJ/m²	570 MJ/m²	570 MJ/m²
Fire Load Energy MJ	9,360 MJ	139,536 MJ	200,925 MJ
Peak Mass Burn Rate kg/s	0.3 kg/s	3.3 kg/s	4.3 kg/s
Peak Mass Burn Rate kg/min	18 kg/min	198 kg/min	258 kg/min
Heat of reaction MJ/s	5.1 MJ/s (5.1 MW)	65.1 MJ/s	86 MJ/s (86 MW)
Heat of reaction MJ/min	306 MJ/min	3906 MJ/min	5160 MJ/min
Steady state duration (min)	11 min	2 min	1 min
Peak HRR (Qmax) MW	5.1 MW	65.1 MW	86.4 MW
Steady State Fire	306 MJ/min x 11 = 3366 MJ	3906 MJ/min x 2 = 7812 MJ	5160 MJ/min x 1= 5160 MJ
FF Water required L/min	5.1 MW x 0.38 = 1.9 L/s x 60 = 116 L/min	65.1 MW x 0.38 = 24.7 L/s x 60 = 1484 L/min	86.4 MW x 0.38 = 32.8 L/s x 60 = 1968 L/min
23 L/MW =	23 x 5.1 = 117 L/min	23 x 65.1 = 1497 L/min	23 x 86.4 = 1987 L/min
FireSys Calculates	2 L/s (120 L/min)	25 L/s (1500 L/min)	33 L/s (1980 L/min)
HEAT EXTRACTION			
Total Reaction Zone (RZ) @ 50% Overall Peak Combustion Efficiency	2.55 MW 2.55 MJ/s 153 MJ/min	32.5 MW 32.5 MJ/s 1950 MJ/min	43.2 MW 43.2 MJ/s 2592 MJ/min
36% Water reaching Flaming reaction zone Gaseous Phase	36% of 116 L/min = 42 L/min (0.7 L/s)	36% of 1484 L/min = 534 L/min (9 L/s)	36% of 1968 L/min = 708 L/min (12 L/s)
64% Cooling efficiency on the flaming fuel surfaces	64% of 116 L/min = 74 L/min (1.23 L/s)	64% of 1484 L/min = 950 L/min (16 L/s)	64% of 1968 L/min = 1260 L/min (21 L/s)
Heat Extraction from reaction zone	153 MJ to be extracted/minute	1950 MJ to be extracted/minute	2592 MJ to be extracted/minute
Water required for RZ = MJ / 3.6 MJ/kg	153 / 3.6 = 42.5 L/min	1950 / 3.6 = 542 L/min	2592 / 3.6 = 720 L/min
The remaining water is used to cool and penetrate the fuel base	74 L/min	942 L/min	1248 L/min

*** This is taken as one single zone (353 m2) of a four-zone (1410m2) travelling fire*

Table 12.11: Typical heat extraction analysis from the flaming reaction zone (gas-phase) of three fires (demonstration examples) based on Karlsruhe University (Germany) data[146].

146 Fuchs. P; On the Extinguishing Effect of Various Extinguishing Agents and Extinguishing Methods with Different Fuels, Karlsruhe University (Germany), *Fire Safety Journal, 7* (1984) 165–175

12.13 A SLIDING-SCALE FLOW-RATE ANALYSIS FOR FIRE COMMANDERS

It is important for fire commanders to be able to roughly estimate the limitations of the amount of firefighting water available on-scene, against a large growing fire. Where a fire in a large floor space with a high fuel load continues to grow, a time may come where the speed of fire development outpaces the quantity of water being applied to the fire and a transition to *defensive mode* of attack may become necessary. Aside from obvious triggers such as unstable structures, inadequate staffing or hazardous storage, a quick analysis of the flow-rate available can determine at what point the fire may begin to outpace safe and effective interior offensive operations.

It can be seen in the upper graph's flow-line (L/min) that as floor area fire involvement increases, so too does the needed (applied) flow-rate increase. This is nothing new to firefighters! Where non-residential buildings are involved the required flow-rate is even greater. Such information presented this way would suggest that as a fire grows larger, we simply apply more water. However, it does not necessarily present a picture of when defensive operations might become necessary. The lower graph (**L/min/m^2**) demonstrates how the ratio of applied flow-rate decreases as the fire size increases.

There is evidence from the research presented in this chapter that suggests when applied flow-rates fall below 4 L/min/m^2 in non-sprinklered compartments, we are entering the '*inadequate water*' phase of fire attack where *total burnout* may ensue. This is the point where the fire is growing faster than we can apply adequate water. This may be because we do not have enough staffing or resources to apply the required amount of water or because we are unable to access the fire area, or perhaps we are unable to transport sufficient quantities of water to the fire scene quickly enough. A rough fire-ground calculation can be made here by taking the total floor area (m^2) involved by fire and multiplying it by 4. If the total floor area of the building is 600 m^2 and 200 m^2 is involved in fire, multiplying 200 x 4 = 800 L/min. This is the minimum flow-rate where we can safely continue offensive firefighting operations, based on flow-rate alone, without placing firefighters in compromising situations (also see table 12.16). However, in reality that 200 m^2 of fire may soon become 300 m^2 if we aren't able to apply water with good effect.

Note: A minimum flow-rate deployment of 200 L/min (High-Pressure) is recommended in UK dwelling fires.

The reader should take note that this research and recommended flow-rates for firefighting or design purposes are the result of 5,401 working fires across all occupancy groups and building types in England, but would generally represent the UK and many parts of Europe in general. In other countries the construction materials, floor space and ventilation factors may vary from those common to this research data and therefore any guidance here should be considered on the basis that both fixed and movable fire loads may present fire intensities that are greater and are therefore likely to affect calculated outcomes.

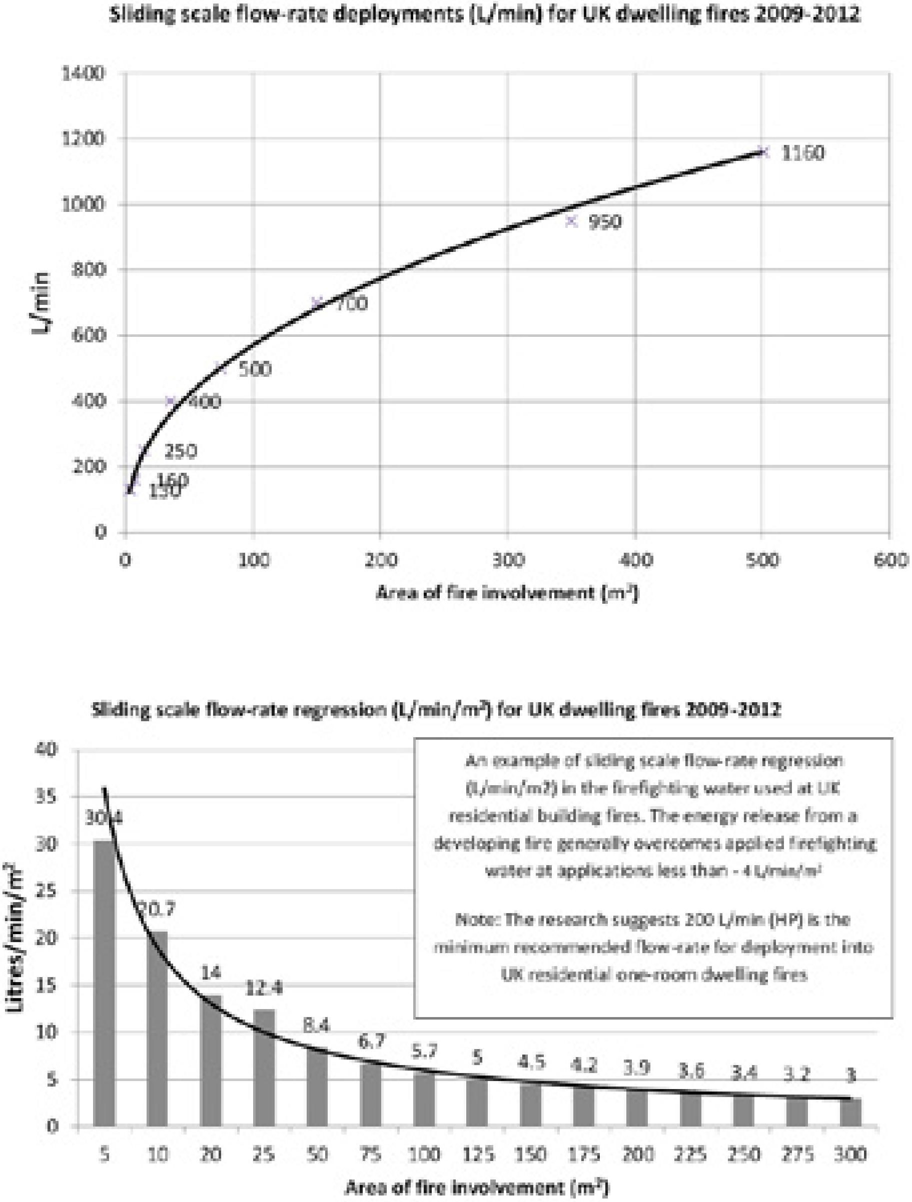


Figure 12.30: Sliding scale deployments and regression graphs of firefighting water (UK dwelling fires)