Fire-fighting Flow-rate

Barnett (NZ) – Grimwood (UK) Formulae

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Introduction

A recent survey of 58 UK fire brigades demonstrated that 89 percent of brigades were actually flowing far less water through their attack hose-lines than they realised and in some cases were flowing as little as 16 percent of their target (nozzle specification) flow-rates! Further still, the influence of CFBT (Compartment Fire Behaviour Training) in the UK has encouraged a dangerous precedent – that *less water* means safer and more effective firefighting! This philosophy only holds true for gaseous-phase fire involvement restricted in area - *up to 70m2 of ordinary hazard fire loading* - where beyond this amount of fire, a 'high flow' hose-line capability is essential for fire control. Situations whereby firefighters are 'pulsing' the smallest of flows into high volume gaseous-phase fires achieve far from the intended objectives of well-founded CFBT programmes and such approaches place firefighters at unnecessary risk.

Firetactics.com are continuing to promote a long overdue transition towards 25mm high-pressure hose-reels and 51mm lay-flat attack hose-lines for the UK fire service. This view is most recently supported by the ODPM –

> *'Fire and rescue services should consider the adoption of 51mm hose instead of 45mm hose for high-rise fighting. This is due to its improved hydraulic characteristics and its ability to supply an adequate firefighting attack from fixed installations, which may not be achievable with 45mm hose. These benefits would also apply to other firefighting applications currently undertaken with 45mm* hose'…***Office of the Deputy Prime Minister (BDAG) December 2004***
>
> **(Effect of reduced pressures on performance of firefighting branches in tall buildings – Hunt & Roberts ODPM 2004)**
>
> *It is worth noting that the crews undertaking the trials identified a number of other benefits when using the 51mm hose. These included improved manual handling and, as the hose was yellow, the ability to locate the hose - and the crews at the end of the hose - when in conditions of low illumination or smoke logging. These benefits would also apply to other firefighting applications currently undertaken with 45mm hose. Furthermore it should be noted this size and colour of hose is readily available in the UK and covered by the same British Standard as other delivery hose…*
>
> **ODPM Fire & Rescue Service Circular 55/2004**

The Need for Higher Firefighting Flow-rates and Larger Diameter Attack Hose-lines in the UK

This paper is designed to demonstrate how firefighting flow-rate requirements have been addressed through recent research projects. It also explains how the current equipment used to transport water onto fires in the UK has gradually evolved into a mismatched system over the past fifty years. The result of this 'mismatch' is that optimal use of firefighting water, utilising modern firefighting tactics, is not being met. The text goes on to examine -

- **How are compartment fires being suppressed using new tactics?**
- **3D attack concepts introduced by Swedish firefighters**
- **Indirect attack methods introduced by US firefighters**
- **Traditional 'direct' attack concepts using modern branches demanding higher nozzle pressures**
- **The science and development of firefighting flow-rate and the need to provide firefighters with safe and effective flows, that will enable them to take control of a fire at an earlier stage in the operation, particularly where using limited resources**
- **International Firefighting Flow-rate research comparisons**
- **The performance of 19mm and 25mm bore hose-reels when firefighting in the gaseous-phase**
- **The capability of 38m, 45mm and 51mm lay-flat hose-lines when firefighting in the fuel-phase**
- **25mm High-pressure hose-reels versus low-pressure lay-flat hose-lines in both the gaseous and fuel-phases of firefighting**
- **Critical flow-rate versus Tactical flow-rate**
- **Heat absorption efficiency of a fire-stream**
- **Fire-ground Formula for estimating needed fire flows**
- **Baseline flows for attack hose-lines**

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The Author

Paul Grimwood is a retired London Firefighter who has researched firefighting flow-rates since 1989. His initial study of 100 working fires in London (Fog Attack 1992) suggested that a substantial percentage of fires were being suppressed during the decay stages of firefighting operations. This is an undesirable approach to structural firefighting, which increases the risk of structural collapse at fires and places firefighters at unnecessary risk.

His proposals for addressing minimum firefighting flow-rate requirements are substantiated by his recent 58-brigade survey that demonstrated 89 percent of UK fire brigades are under-flowing their attack hose-lines in failing to meet the optimal performance criteria of firefighting nozzles currently in use.

His earlier research has been used by Cliff Barnett, a world-renowned firefighting flow-rate expert, to update fire stream efficiency factors. The updated TP 2004/1 document produced for the New Zealand SFPE and the combined research projects are discussed in this paper.

1. Compartmental Fire Attack Concepts

Mechanisms of Fire Extinction

- **Fuel Cooling** - *Cooling of the combustible solid fuel surface*, which reduces the rate of pyrolysis and thus the supply rate of fuel to the flame zone. This reduces the rate of heat release by the fire; consequently the thermal feedback from the flame is also reduced and this augments the primary cooling effect of the suppression agent. The application of a water spray to the fuel bed is typical of this method although a straight-stream, or smoothbore attack, may be equally effective, if not more so.
- **Flame Cooling** - *Cooling of the flame zone directly*; this reduces the concentration of free radicals (in particular the chain-branching initiators of the combustion reaction). Some proportion of the heat of reaction is taken up by heating an inert substance (such as water) and therefore less thermal energy is available to continue the chemical break-up of compounds in the vicinity of the reaction zone. One function of the latest water mist technology is to act in this manner; the fine droplets providing a very large surface area per unit mass of spray in order to increase the rate of heat transfer;
- **Flame Inerting** - *Inerting the air feeding the flame* by reducing the oxygen partial pressure by the addition of an inert gas (e.g. N_2, CO_2, vapor). This is equivalent to the removal of the oxidizer supply to the flame by the production of water vapor and is the dominant mechanism by which the Layman/Royer/Nelson concepts of indirect water fog attack achieve suppression. In a discussion of fixed system water-mist fire extinction mechanisms, Mawhinney (1) added to the above three mechanisms some further effects associated with *decreasing thermal radiation, dilution of the flammable vapor/air mixture, and chemical inhibition* as playing a part in fire suppression.

MECHANISM OF EXTINCTION	METHOD OF SUPPRESSION	ESTIMATED PERCENTAGE OF USE
FUEL COOLING	DIRECT ATTACK	95% Structure Fires
FLAME COOLING	3D OFFENSIVE ATTACK	40% Structure Fires
FLAME INERTING	3D DEFENSIVE ACTION	85% Structural Fires
FLAME INERTING	INDIRECT ATTACK	5% Structure Fires

Table 1 – Mechanisms of fire extinction; methods of fire suppression; and estimated percentages of use for each suppression tactic at UK structure fires (*3d Firefighting - Grimwood; Hartin; McDonough & Raffel - FPP/IFSTA Oklahoma State University USA 2005)*

Two Types of Structural Enclosure Fires

A compartment or enclosure fire involves a room or space within the confines of a structure. A fire involving two, or several, rooms/spaces is said to be a multi-compartment/enclosure fire. A fire that has developed beyond the definitions of compartmental, where elements of the structure have been breached and have become involved in fire, is said to be 'structural'. Based upon the above mechanisms of fire extinction, there are two basic types of combustion that the firefighter may face in almost every compartment/structure fire, namely:

- **Fuel-Phase Fire** - *Two-dimensional* fuel bed or surface fire (m2)
- **Gaseous-Phase Fire** - *Three-dimensional* gaseous-phase fire (m3)

While all firefighters are able to think in two-dimensional terms and apply traditional water applications to the fuel-phase fire, how many are able to view a fire three-dimensionally and utilize techniques to counter hazards involving the gaseous-phase? Also, what about the exposure risk? The idea that accumulating fire gases in the overhead, or in adjacent or non-adjacent compartments, are creating an exposure risk is rarely considered by firefighters.

There are three methods of fire suppression using water that may be utilized to deal with the above two types of fire:

- **Direct Attack** – The traditional approach that deals with the majority of fires. This method relies on a stream of water to cool the fuel-surfaces involved in fire when applied directly onto them where the application of water is quantified in lpm/m2.
- **Indirect Attack** – A method of applying water fog onto super-heated surfaces in the fire compartment to create a mass of steam that displaces the oxygen to smother the fire. This approach, based upon the principles of Lloyd Layman (USA) and commonly known as the 'Iowa' or 'Royer/Nelson' method (2), is normally applied from an exterior position. When applied under strict protocols this method is extremely effective in certain situations and may deal with combustion in both the fuel and gaseous-phases.
- **3D (three-dimensional) 'Offensive' Water Fog** - A method introduced by Swedish firefighters (3) during the early 1980s, using controlled nozzle pulsing actions or brief bursts of water fog to counter combustion in the *gaseous-phase (offensively).* This approach may also be used (*defensively*) to prevent/mitigate the effects of flashovers, backdrafts, or other ignitions of the fire gases. The term 3D (4) refers to the *volumetric* mechanisms of combustion in the gaseous-phase and associated water applications are normally calculated in cubic dimensions (lpm/m3).

2. The Science of Firefighting Flow-rate

The concept of CFR relates to the '*minimum amount of water-flow (lpm/m2) needed to fully suppress a fire whilst still in a state of development*, *or possibly during a progressive decline into its decay phase'*(5). Where a compartment/structural fire exists in its *growth-phase* the heat output will be constantly increasing and the amount of water needed to extinguish the fire effectively will be much higher than where the fire has progressed beyond 'steady-state' combustion into a *decay-phase* of burning. There have been several international research studies that have attempted to calculate both firefighting flow-rates and critical flow-rates. It is important to realize that critical flow-rates (CFR) may vary, dependant on the style of attack. The CFR for a direct attack on the *fuel-phase* will be different to an attack on the gaseous fire. Similarly, a fire's rate of heat release may be influenced by the ventilation profile and this in turn may affect the CFR in any specific compartment. It is therefore equally important to approach various formulas used to calculate firefighting flow-rates with these points in mind. When comparing flow-rate formulae it is important also to consider their origins and objectives as each approach is intended to deal with a specific range of fire conditions and mechanisms of fire suppression.

Ever since I began my research into fire-fighting flow requirements in 1989(6) I have strived to calculate the most reliable estimate for fire-fighters to use when forming their tactical approaches at structural fires. It was obvious to me that existing flow-rate formulae at that time were far too broad, or theoretical, and those that have evolved since have often been flawed in some sense, or are far too complicated in their practical approach. It was my intention to provide an easy to use fire-ground formula based on empirical research data recorded across many hundreds of live fires, in both test and real world situations. In 1999 I introduced and defined the concept of *Tactical Flow-Rate* (TFR)(7) in my research, being the target flow for general firefighting operations. This calculated fire-ground estimate proved reliable for fires between 50m2 - 600m2 in area.

In December 2004, New Zealand Fire Engineer Cliff Barnett turned to my earlier practical work and fire-ground formula to update his own world-renowned *efficiency factors*, used by the Society of Fire Protection Engineers (NZ), for predicting fire-fighting flow in designed engineering based applications. The resulting document SFPE (NZ) TP 2004-1 offers in my opinion, the most accurate fire-fighting flow-rate requirements for use by both fire-fighters and design engineers to date. My original research project evolved without any outside influence from other internationally accepted methods of calculating fire flows but the final approach appeared closely linked with, and somewhat in confirmation of, both the IOWA(2) and the NFA(8) formulae in the USA. Both of these formulae approach fire flows from totally different perspectives and result in widely varied *Needed Fire Flows* (NFF), so a link to both seems strange. However, my own formula takes into account firefighting in both the *fuel-phase* and the *gaseous-phase*, which few other formulae attempt, and therefore accounts for firefighting flow requirements in more general terms.

Critical (CFR) & Tactical (TFR) Flow-rates

▪ **Critical Flow-rate (CFR)** – The CFR refers to the 'minimum amount of water-flow (lpm) needed to fully suppress a fire at a given level of involvement' (ie; during growth or decay stages of development). The actual CFR for compartment fires of a given size (m2), existing in different stages of fire development, may be widely variable.

▪ **Tactical Flow-rate (TFR) –** In theoretical terms of simply *meeting* a critical rate of flow, Sardqvist (9) reports that this does not offer the best use of resources, as it requires a more or less infinite time. An increase in the flow-rate above the critical value causes a decrease in the total volume of water required to control the fire. However, there exists an *optimum flow* giving the smallest total water volume. Above this flow, the total volume of water increases again. In practical terms however, a margin of safety, or error, must be designed into the application of any firefighting tactic and this includes methods of fire suppression and flow-rate. An increase in water flow will generally darken a fire quicker. However, there is an upper limit on flow-rate in terms of what is practical for any given size of fire, inline with the resources available on-scene during the early stages of primary attack. The author's (Grimwood) *tactical flow-rate* is the target flow (lpm) for a primary attack hose-line/s. It is based upon extensive research and empirical data relating to firefighting flow-rates in several countries. The *tactical flow-rate* discussed in this text is for fire suppression during the growth phases of development, or in post-flashover *steady state* enclosure fires before the decay-phase has been reached. It is always an operational objective to achieve control during the growth stages of a compartment fire's development, rather than during the latter decay stages, to reduce the chances for serious structural involvement and any potential collapse, particularly where an interior approach is made.

The concept of fire-fighting flow-rate requirements can be theoretically based in matching water-flow against known rates of heat release (MW) in compartment fires. It can also be empirically based upon given fire loads, in established floor space, against water flows needed to suppress fires during their growth or decay stages (the latter generally being a defensive application). In my own sixteen-year research project I have used both methods and eventually combined them to produce a tactical flow-rate formula of proven reliability. Going beyond *critical flow-rates* (the minimum amount required) the *tactical flow-rate* incorporates an element of 'safety' and 'over-kill' whilst aiming for an optimal flow of water that will deal with most fires of 'normal (ie; office)' fire load during their growth stage of development without unnecessary water damage.

The application of water to a Class 'A' compartment fire achieves extinction by a combination of mainly three mechanisms. The influence of each mechanism in the overall extinction of the fire is dependent on the method of delivery of the water. These mechanisms are defined above.

It should be noted that there are also references here to the National Fire Academy (NFA) and Iowa (Royer/Nelson) methods of determining an ideal flow-rate for structural firefighting. However, these formulae and calculations refer *only a single method of fire suppression* – NFA (direct attack) and Iowa (indirect attack); whereas the proposed *tactical flow-rate (TFR)* for specific approaches to interior attack is adjusted to accommodate all three methods of fire suppression as discussed above. This results in a recommended *base-line flow* as discussed later. Although the TFR is designed with an inbuilt margin of error and safety it does not view a back-up/support hose-line as part of the primary attack lay-in, as the NFA calculation does. Whilst such a strategy is to be encouraged at the earliest opportunity a support hose-line is generally seen as a *secondary* action and its prompt placement will depend upon crewing levels on the initial response.

Water Spray, Fog or Mist? – Definitions

The use of fine water droplets for *gaseous phase* fire suppression has been studied for at least fifty years. There is a need for consistent terminology when discussing firefighting sprays, especially when considering the characteristic 'size' of the droplets. Average sizes of droplets that appear of most interest in firefighting terms (hand-held attack hose-lines) fall within the range of 100-1000 microns (0.1-1.0 mm). A spectrum of *drop sizes* classes them into five categories –

Colloidal	Below 1 micron - appears as smoke
Dust	Between 1-10 microns - appears as oil or sea fog
Fine	Between 10-100 microns - appears as clouds or mist
Average	Between 100-1000 microns - appears as drizzle or rain
Coarse	Between 1000-10000 microns - appears as coarse heavy droplets

Table 2 – A spectrum of water droplet sizes – 1000 Microns = 1mm diameter

In firefighting terms the size of an individual droplet, or some mean drop size within a spray, is of great importance when discussing other attributes of the spray as the resistance offered by the surrounding air to the forward motion of the droplets is proportional to the droplet diameter. Therefore the carrying power, or penetration, of the spray is strongly dependant upon the drop size distribution. The efficiency of heat transfer to water droplets, which is fundamental to their use in firefighting applications, is also dependant on droplet geometry and in particular the ratio of the total surface area of the spray to its volume; maximising this ratio is beneficial in promoting rapid absorption of heat from the environment and subsequent evaporation of the droplet. The practical penetration achieved by a particular spray is governed by the relative magnitudes of the kinetic energy of the initial liquid and the degree of aerodynamic resistance offered by the surrounding gas. All other things being equal, the penetration of a spray is much greater than for an individual drop, since the *leading droplets* impart forward momentum to the surrounding gas, reducing the air drag on the following drops and thus creating a 'pathway' for them, resulting in better overall penetration. There is a growing body of contemporary research concerned with the interaction between water droplets and buoyant fire plumes. This literature(1) suggests there may exist a critical heat release rate above which a given drop size would not contribute to fire extinction due to its failure in reaching the relevant 'cooling' zone.

Advantages of Optimum Droplets and High Velocity Fog Streams

The Annual Building Fire Research Laboratory (BFRL) Conference on Fire Research in 1998 produced an interesting (NIST) paper (10) that investigated the *Mitigation of Compartment Jet Fires Using Water Sprays.* The main objective of the study was to investigate the interaction of water-sprays with a burning gas layer at the ceiling, in a ventilation controlled state, and close attention was paid to the effectiveness of different spray angles, droplet diameters, stream velocities and water flow-rates. Although the directions of sprays were downward, from the ceiling in this study, the mechanisms associated with *flame cooling* were of direct relevance to 3D applications by firefighters. It was generally observed that water applications into the gas layers utilising different spray angles of 30, 60, 75, 90, 120, 135 and 150 degrees produced varying reductions in compartmental temperatures but spray cones within the 60-75 degree range were found to be most effective in reducing the overall temperature. For these angles the limiting behaviour due to the effectiveness in penetrating the flame indicated that spray velocities in excess of 18 metres/second (40 mph) should be used. The mean droplet diameters of 100 to 600 microns were analysed and it was further noted that droplets within the 300-micron (0.3mm) range maximised any cooling effects within the compartment. In terms of flow-rate it was reported that, for these compartmental dimensions of 115m2 the '*most efficient'* flow-rate (for gaseous-phase suppression) was around 113lpm where 0.3mm droplets formed the main bulk of the spray pattern. This equates close to one litre per m2 (1l/m2) and correlates closely with the critical flow-rate (CFR) recorded in the Svensson and Sardvqist research detailed below. The term 'most efficient' seems to border the CFR and would not be seen as 'optimum' flow-rate in practical terms, particularly in dealing with fire in the fuel-phase.

Rasbash (11) further attempted to estimate the heat transfer between flames and water sprays and produced a plot of *convective heat transfer rate* against *drop velocity* for drop sizes ranging from 50 microns to 2mm whilst assuming a flame temperature of 1,000 deg C. In general, higher velocities and smaller droplet diameters were found to increase the heat transfer rates. For example, a 2mm droplet at 0.07m/s (terminal velocity in still air) produced a heat transfer rate of 167 kW/m2 while the same droplet travelling at 2 m/s achieved a value of 293 kW/m2. For a 50-micron drop at velocities of 0.01 m/s and 0.5 m/s the corresponding heat transfer rates were 1.7 MW/m2 and 2.5 MW/m2 respectively. It is this high-velocity application of fine water droplets that make HP hose-reel systems of 25mm diameter bore so effective in the gaseous-phase. An estimation of droplet penetration was also studied in the research and it was noted that drops of larger initial size were able to penetrate further into the flame before complete evaporation occurred.

Dealing with Combustion in the Gaseous-phase

When a water spray pattern passes through the hot gases, heat transfers to the droplets, which then start to evaporate. As we have seen above, evaporation depends to a great extent on droplet diameter, temperature, and transport properties (velocity etc).

- Sprays made up of smaller droplets present a larger surface area in relation to their volume and so heat up and evaporate faster, consequently absorbing more heat. Small droplets will evaporate quickly and will concentrate their suppressive effect on combustion occurring in the *gas-phase*.

- Large droplets will not entirely evaporate when passing through flames and hot gases, unless the flames are very deep, which usually is not the case in apartment fires. Instead, these droplets will mostly pass through the flames and collide with the burning material, or other superheated surfaces, causing a decrease in pyrolysis.

When water droplets travel through the gaseous-phase of a fire there is much heat and mass transfer between droplet and hot gas. There is also an element of 'drag' upon the droplets that will affect their velocity and trajectory. All these factors affect a droplet's ability to absorb heat from the gases. The fire's plume and convection currents within an enclosure also have a major effect upon the movement of droplets that are too small (below 0.1mm), where they may be simply carried away before they are able to have any great cooling effect.

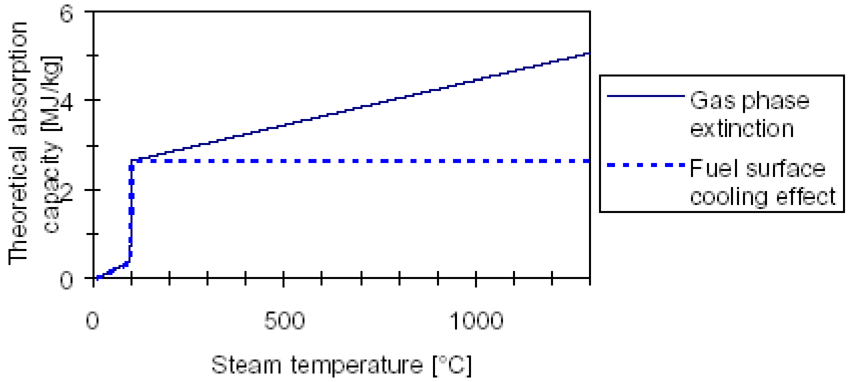

Fig 1 - Theoretical heat absorption capacity of water in the gaseous-phase and on surface cooling.

There is a wealth of scientific and empirical research that attempts to define the ideal droplet size for use in manually applied firefighting streams. The general consensus is agreed that droplets falling within the mean range of 0.2mm - 0.4mm diameter provide the greatest effect in terms of 3D gaseous-phase cooling, dilution and suppression. The mean droplet diameters found in spray patterns provided by many of the world's combination fog/straight stream firefighting nozzles, when operated at 7 bars NP, generally fall within the 0.4mm – 1.0mm range. As nozzle pressures (NP) and stream velocities are increased the median droplet diameter decreases closer towards the 0.3mm ideal level. The higher nozzle pressures associated with 25mm HP hose-reel systems are what make this fire stream more effective than some low-pressure streams using lay-flat hose, flowing more water. The breakdown in droplets to around 0.2mm, and the greater velocity associated with 25mm HP hose-reel systems, serves to increase the fire suppressive performance as seen in the Svensson and Sardvqist research as reported later. The much lower nozzle pressures and poor stream velocities achieved when using 19mm bore hose-reels generally only produce droplets within the 0.4-1.0mm range and the fire suppressive performance is therefore not as good when using lower flows.

Although in general, smaller droplets are undoubtedly more effective in the gaseous-phase, the slightly larger droplets are able to *reach and cool* boundary and fuel surfaces more effectively, preventing rapid reheating and ignition of fire gas accumulations. One observation during a range of tests (4) showed that, when discharged into the gaseous-phase, larger droplets cooled the enclosure walls more effectively –

● 0.3mm droplets cooled boundary wall by 57degC within two minutes

● 0.7mm droplets cooled boundary wall by 124degC within two minutes, and

● 0.8mm droplets cooled boundary wall by 195degC within two minutes

This observation demonstrated and confirmed some interesting points –

● More cooling power reached the enclosure boundary when larger droplets were in use.

● More cooling power was utilized in the gaseous-phase when smaller droplets were applied.

● The application of larger droplets causes *more evaporation (steam expansion) on the enclosure boundary but less evaporation (and contraction) in the gases*. This imbalance is generally undesirable and serves as the root cause of much opposition to water-fog tactics by firefighters who have sometimes experienced steam burns from over zealous applications.

The National Research Council (NRC) Canada presented some interesting research data (12) as follows -

The performance of the 3D water-fog attack strategy is generally determined by the nozzle characteristics (e.g., droplet size and velocity, spray angle, and flow rate), and application techniques (e.g., discharge angle, and duration of discharge). When using the 3D water fog technique *(into the gaseous-phase),* the nozzle and application technique are different from those used in the direct and indirect attack methods. In theory, small droplets are more efficient in cooling and diluting the gases than large droplets, because of the larger total surface area available for evaporation and heat extraction. When the droplet diameter is reduced from 1.0mm (1000um) to 0.1mm (100um), the total surface area increases 10 times from 6 m^2 to 60 m^2 for 1 liter of water. However, on occasions, droplets may be so small that they are blown away on the convection currents before they are able to effectively take part in any cooling process.

The cooling effectiveness of water spray for hot gases is also determined by the residence times of droplets that are available for absorbing heat from the gas. The longer the residence time, the better the cooling effectiveness of the spray. The residence time of various droplet patterns can be roughly assessed in still air by 'pulsing' a brief burst of water-fog into the air. It can be seen that an effective fog pattern suited to a 3D application will discharge a range of droplets that demonstrate a visible residence time in air of around 4-6 seconds before striking the ground.

ΔT (°C)	100 (μm)	200 (μm)	300 (μm)	500 (μm)	1000 (μm)
200	0.8 s	1.6 s	2.4 s	4.0 s	8.0 s
300	0.533 s	1.06 s	1.6 s	2.66 s	5.33 s
400	0.4 s	0.8 s	1.2 s	2.0 s	4.0 s
600	0.26 s	0.52 s	0.78	1.3 s	2.6
800	0.2 s	0.4 s	0.6 s	1.0 s	2.0 s
1000	0.16 s	0.32 s	0.48 s	0.8 s	1.6 s

Table 3 – Lifetime (seconds) of water-droplets with temperature – *National Research Council Canada RR124 (2002)*

This will represent the 'typical' fog pattern consisting of a droplet range within the 0.2-0.4mm range (for manually applied firefighting streams). Under fire conditions this actual *residence time* of droplets is relative to the temperature of the gases and the size of the droplet (table 3). For example, 1.0mm (1000um) droplets passing through an upper gas layer heated to 600degC will exist for 2.6 seconds (table 3) before evaporating entirely. In small compartments the larger droplets will reach boundary walls, ceiling and linings, causing excess steam. In larger compartments the smaller droplets evaporate within a few feet of the nozzle and the effect is lost for the outer reaches of the compartment. Therefore, it is essential to understand the variables of droplet sizing and flow-rate in compartments varying in size up to and beyond 70m2.

How much water is in a 'pulse' or 'burst' from a nozzle, applied in 3D fashion? That depends upon the flow-rate, *how long* the flow-control is 'cracked' open and also by *how much* the flow-valve (ball/slide) is opened. Nozzle 'pulses', or bursts, may vary between short, medium and long in duration. The briefest pulse of water from a *partially opened* nozzle may be just half a second long and discharge around 0.2 litres of water into the overhead – that's a cupful of water! A three-second burst from a *fully opened* nozzle discharging 570lpm flow-rate might place around 28 litres of droplets into the overhead. The variance can clearly be seen. The nozzle operator must be trained to read fire conditions correctly and adjust their applications of 3D water-fog to suit each specific situation, avoiding excessive use of water-fog where necessary.

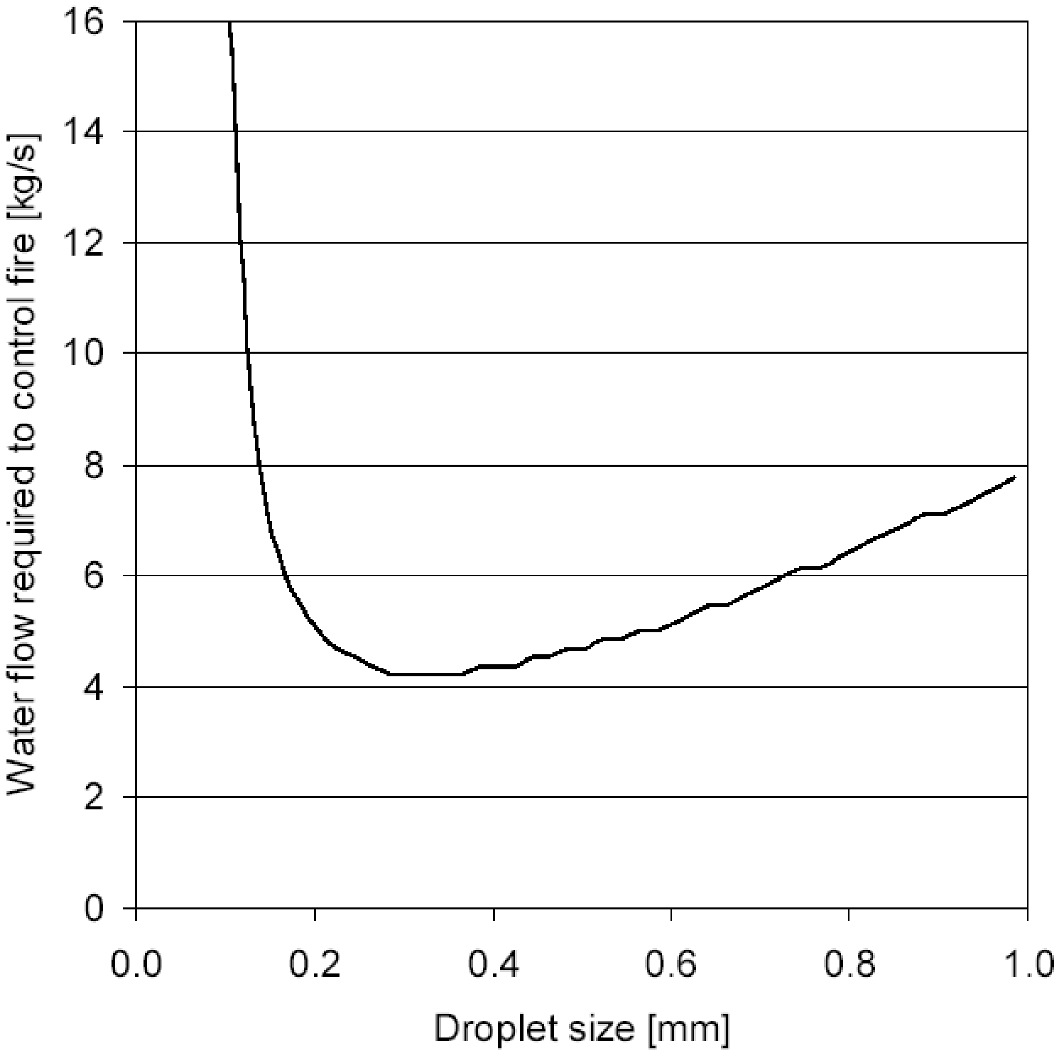

Fig 2 – Svensson & Sardqvist (Lund University, Sweden) use a computerized Fire Demand Model (FDM), (Piertzak, L. M., Dale, J. J – NIST USA), to demonstrate the relationship between water demand and water droplet size for the live-fire test scenario in a 60m2 compartment as described below. As the droplet size above 0.4mm increases, so too does the water flow required to control the fire. *Fire tests in a large Hall - Svensson & Sardqvist Report LUTVDG/TVBB-1025-SE Lund University Sweden 2002.*

High-pressure Hose-reels versus Low-pressure Lay-flat Attack Lines

There has been some detailed comparative research (13)&(14) into the use of high-pressure (35 bars at pump) hose-reel systems versus low-pressure lay-flat-hose (7 bars at nozzle) systems. There are definite advantages of hose-reel systems in that they are extremely lightweight, easy to maneuver and rapidly deployed, although they are generally limited, through friction losses, to a maximum effective 60m lay from the appliance. They are also effective in preserving the available tank water on arrival and during the initial stages of fire attack. However, the low-flow 19mm high-pressure hose-reel systems have been subject to major reviews over the past few years and the performance capability has been in question.

It is most interesting to note that the larger 25mm high-pressure hose-reels are able to outperform the 340lpm 38mm low-pressure lay-flat hose-lines. Svensson and

Sardqvist resorted to some very intense compartment test fires to demonstrate that 50 percent of the flow (LPM) from a 25mm high-pressure hose-reel is potentially twice as effective, compared to 38mm low-pressure lay-flat hose, when applied manually into the *gaseous-phase* using pulsed nozzle applications.

An initial series of tests compared attack techniques in a 12 × 5 × 2.5-m flashover simulator with a 2.5 × 1.1m opening, and a fuel load of approximately 18m2 of 18mm thick particleboard applied on the walls and in the ceiling at the far end of the room, the 25mm 175lpm high-pressure hose-reel was far more effective in dealing with the gaseous-phase fire than the 340lpm 7 bar NP standard 38mm lay-flat attack line when using nozzle pulsing, or brief spray burst, tactics.

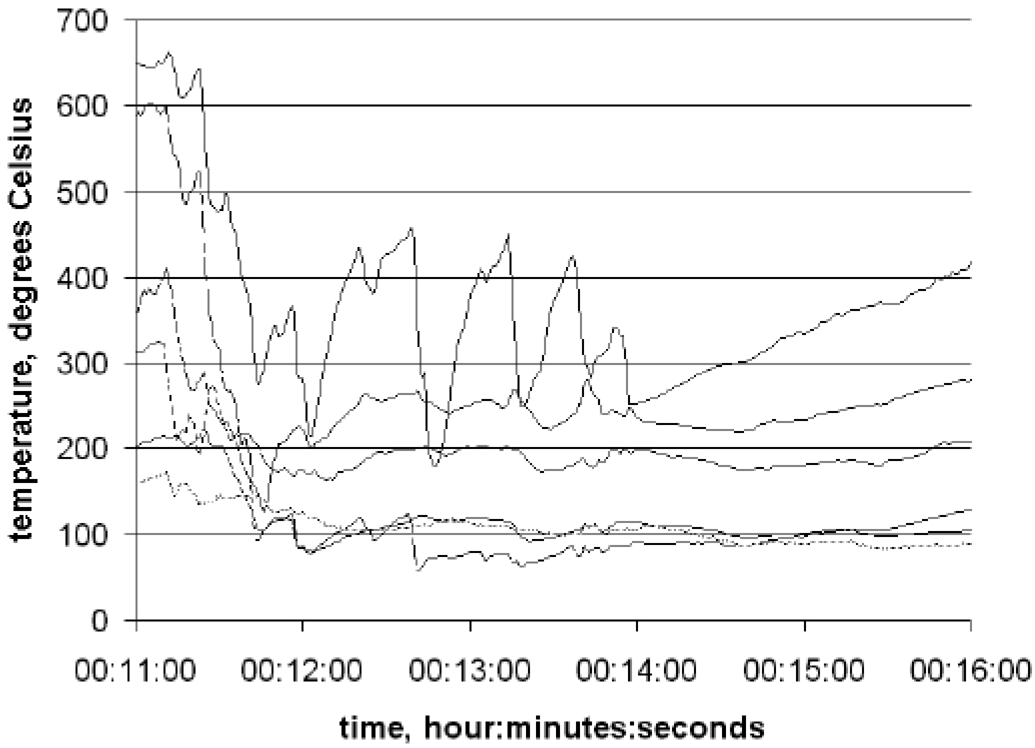

Fig 3 – 175LPM high-pressure 25mm hose-reel demonstrating a 0.2mm mean droplet diameter during 'pulsing' applications into the gaseous-phase using 0.5s – 2s pulses – reducing the upper layer temperatures by more than fifty percent through the evolution (six temperature gradients recorded through the thermal layer). *Svensson & Sardqvist Report LUTVDG/TVBB-1025-SE Lund University Sweden 2002.*

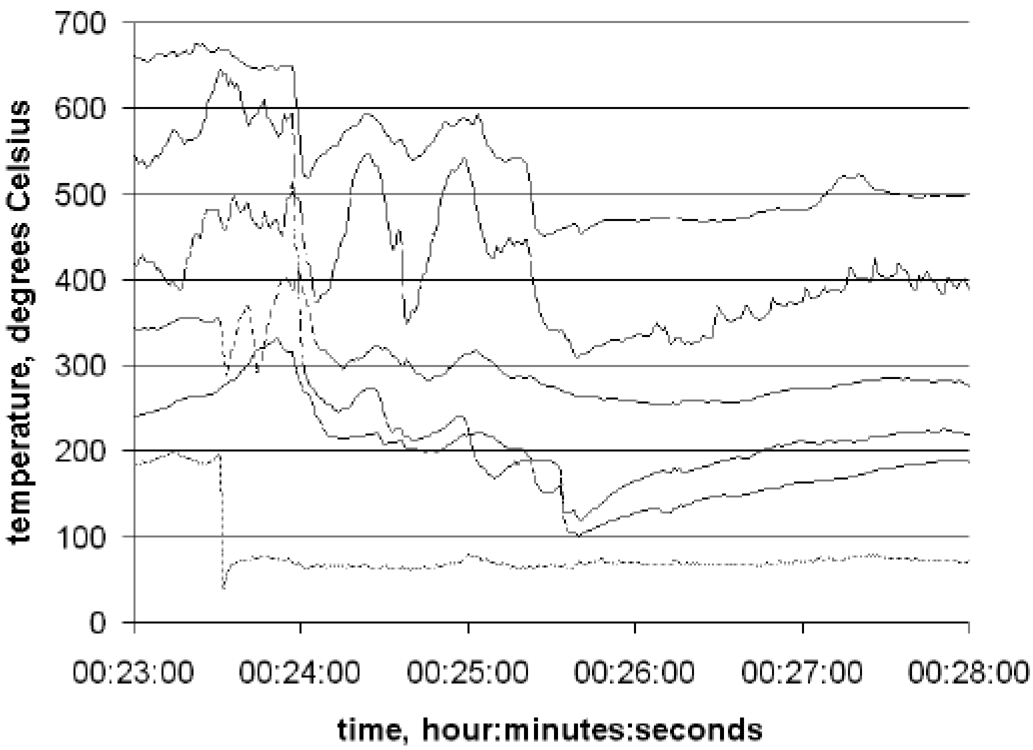

Fig 4 – 340LPM standard 38mm lay-flat attack hose-line demonstrating a 0.7mm mean droplet diameter during 'pulsing' application into the gaseous-phase using 0.5s – 2s pulses – failing to reduce the upper layer temperatures effectively (six temperature gradients recorded through the thermal layer). *Svensson & Sardqvist Report LUTVDG/TVBB-1025-SE Lund University Sweden 2002.*

In a further series of live-fire tests Svensson and Sardvqist went on to compare the effects of 25mm high-pressure hose-reels against ordinary 38mm lay-flat low-pressure hose-lines in tackling a much larger fire involving both the gaseous-phase and fuel-phase fire itself. Tests were performed in a room measuring 14.0 x 7.7 x 6.3m in height. The fuel in each test consisted of 78 wooden pallets arranged in 6 stacks with 13 pallets in each stack.

Data from fuel weight-loss, gas temperature, heat-flux and room pressure were all measured, as were data associated with the physiological effects of heat stress on firefighters. Two different nozzles (Protek style #366 low-pressure nozzle and an Akron Force style 751 high-pressure nozzle) were used. The nozzle pressures were 7 bars (low-pressure) and 25 bars (high-pressure) and the flow rates were 113, 226 and 340lpm. Firefighting was performed manually, and the firefighters were instructed to act in the same way during each of the tests. The same two firefighters, both of them well-trained professionals, took part in all tests. They had the same assignment in all tests. The attack route was through the doorway, advancing into the room parallel to the radiation shield, and then turning left and advancing straight towards the fire along the centerline of the room. On a level with the first radiometer (S2), a short sweep was made with the water spray, 45° upwards, in order to cool the gaseous-phase fire. Three meters from the fire, on a level with the second radiometer (S1), the firefighter with the nozzle halted and started to work on the fuel-phase fire in the stacks of wood pallets

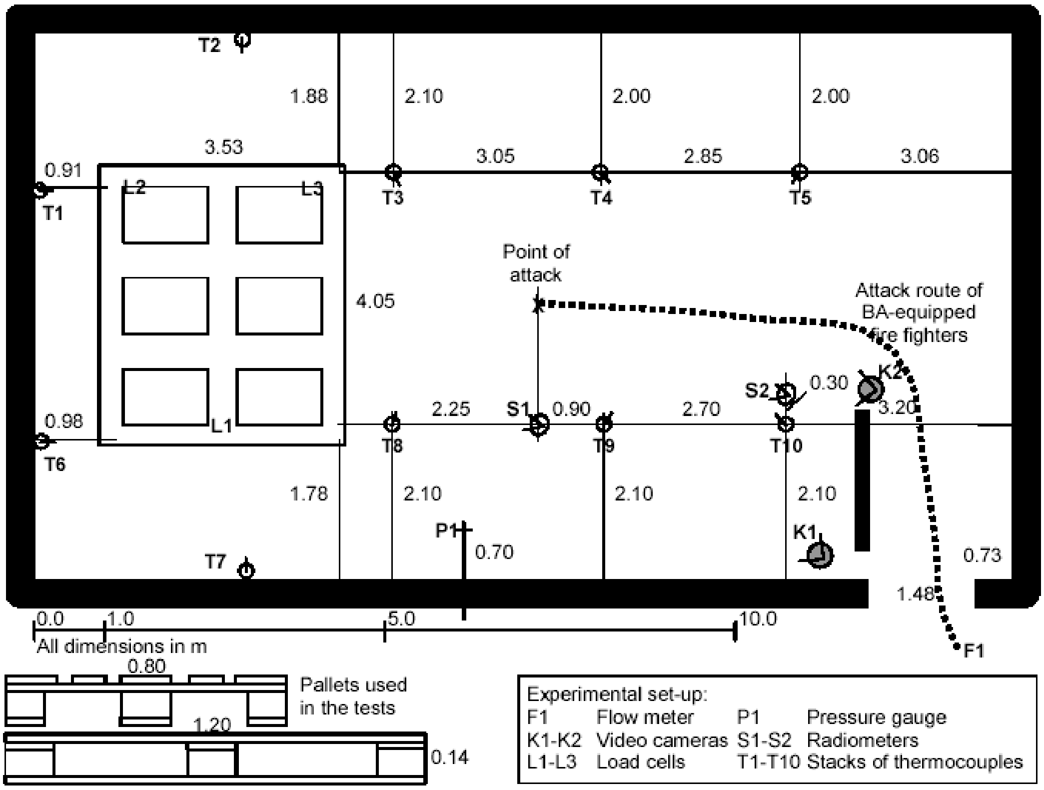

Figure 5 – The test set-up for the second series of tests in a 100m2 compartment (Svensson & Sardqvist) - *Svensson & Sardqvist Report LUTVDG/TVBB-1025-SE Lund University Sweden 2002.*

Considering both (a) fuel surface cooling effects and (b) gas phase extinction effects, the 25mm high-pressure hose-reel system proved to have a better extinguishing capacity *per unit mass of water* than the 38mm low-pressure lay-flat hose system. Regarding fuel surface cooling effects, the 25mm high-pressure system, at a flow rate of 226lpm, was equally efficient as the low-pressure system at 340lpm. The gas cooling effect of the high-pressure system at its lowest flow rate was higher than the low-pressure system at all flow rates. When steady state burning was reached, the high-pressure system at 113lpm stabilized the gas temperature in the room at the same temperature as when the low-pressure system was employed at both 226lpm and 340lpm. Under these test conditions, ***the high-pressure system only required approximately two-thirds of the water of the low-pressure system for the same extinction capability.*** The flow rate of 113lpm was, however, not sufficient to attain the control criterion (6 minutes) of the main fire, based on mass loss rate. At 226lpm, both systems were able to attain the control criterion. ***These were serious compartment fires presenting average burning rates of 5gm2/s and estimated rates of heat release around 16 MW.***

	Water spray characteristics			Water required to control the fire			
Test	Pump pressure [bar]	Nozzle pressure [bar]	Nominal flow [kg/s]	Time [s]	Total mass [kg]	Norm. Mean flow [kg/m²s]	Norm. total mass [kg/m²]
1	7.0	6.0 ± 0.5	3.83	*	*	*	*
2	39	25 ± 5	3.83	210	253	0.00608	1.28
3	7.0	6.0 ± 0.5	3.83	240	286	0.00693	1.66
4	5.2	4.5 ± 0.5	1.92	360 **	303 **	0.00479	1.76 **
5	35	23 ± 5	1.92	360 **	255 **	0.00404	1.48 **
6	8.0	7.0 ± 0.5	5.75	130	152	0.00680	0.88

	Water used overall during attack				
Test	Total mass [kg]	Mean flow [kg/s]	Number of sweeps [-]	Mass per sweep [kg]	Capacity used [-]
1	83	1.52	8	10.4	0.40
2	694	1.46	62	11.2	0.38
3	692	1.26	42	16.5	0.33
4	298	0.843	26	11.5	0.44
5	284	0.708	28	10.2	0.37
6	755	1.50	35	21.6	0.26

* Test halted after initial attack.

** Did not reach the control criterion within six minutes.

Figure 4 – Amounts of water used during the tests - *Svensson & Sardqvist Report LUTVDG/TVBB-1025-SE Lund University Sweden 2002.*

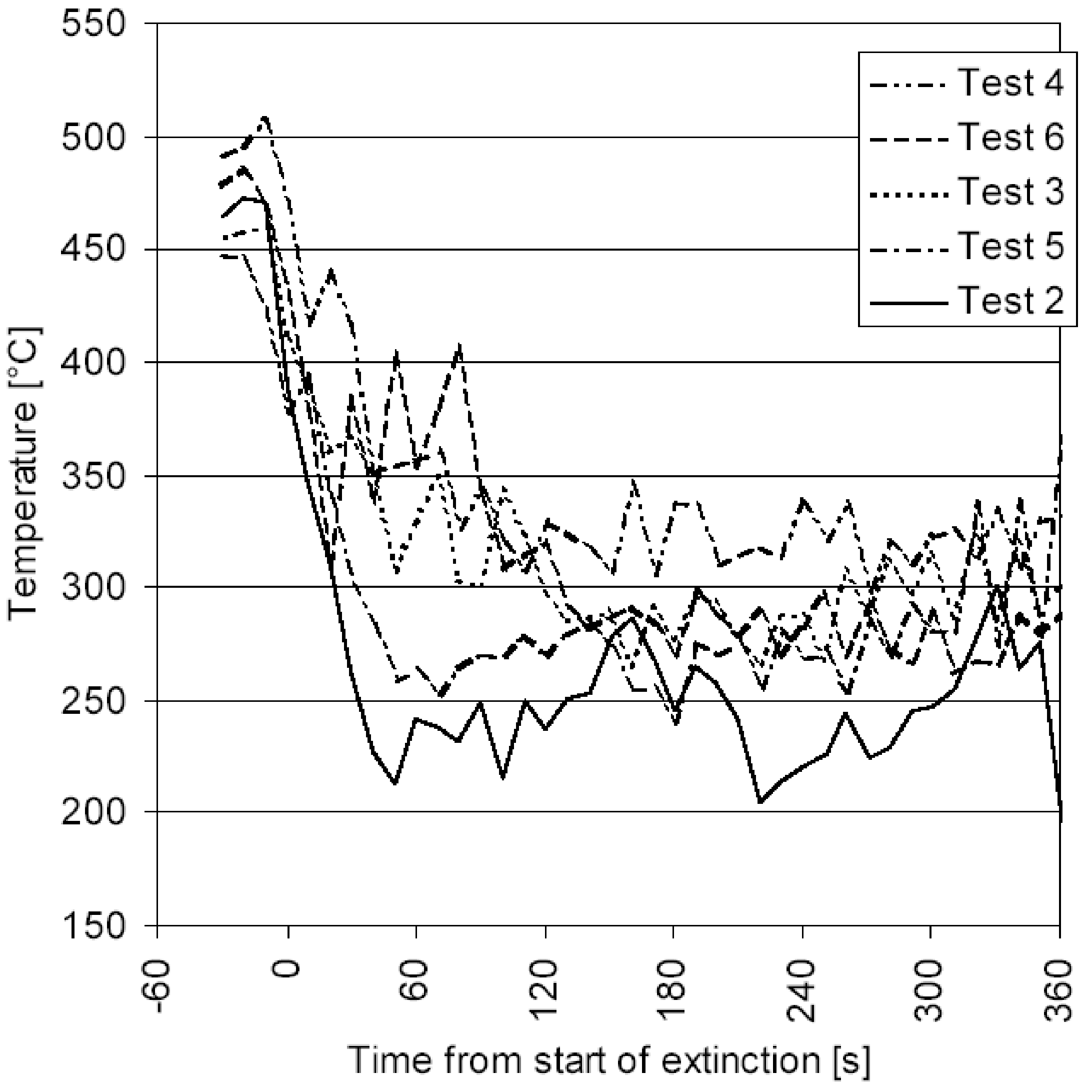

Figure 6 – The mean gas temperatures for all tests clearly demonstrate the greatest cooling effects were achieved during tests 2 & 5 (25mm high-pressure hose-reel) – although the flow-rate (113lpm) used in test 5 was unable to attain final control of the fuel-based fire within the test criteria of six minutes - *Svensson & Sardqvist Report LUTVDG/TVBB-1025-SE Lund University Sweden 2002.*

Critical Flow-rate research

It may be that 25mm diameter 'high-pressure' hose-reel systems clearly offer distinct advantages in comparison to 38mm lay-flat 'low-pressure' hose systems, in limited primary attack situations (80 percent of fires) that deal with combustion in both the gaseous-phase and fuel-phase, or where a rapid tactical deployment of a hose-line working purely off a limited tank supply is needed. However, the concept of *critical flow rate (CFR)* is of great importance when dealing with escalating fire fronts and during deployment of *direct attack* streams to suppress large fires. Where a fire has the potential to demonstrate a rapid development and escalate beyond the limitations of a 226lpm high-pressure hose-reel flow, then greater quantities of water or suppressant are needed in advance. Additionally, tactical concepts such as early placement of secondary support hose-lines, particularly in situations such as basement fires, must be an early consideration.

In 1999(9) Sardqvist reported that the minimum water application rate for *direct* extinguishing, based on experiments using wooden fuels, is 0.02kg/m2 per second. If you consider a compartment of 100m2 (10x10m) then this equates to 120lpm as the *minimum* flow-rate for such an area & fuel-load (wood). Interestingly, that 100m2 is approximately equal in dimensions to the room fire used by *Svensson & Sardqvist* in the above test scenarios and whilst the room was not fully involved in fire, the concentrated fire loading easily represented a fire of similar proportions to a fully involved room. The flow-rate of 113lpm was not sufficient to attain the control criterion (within 6 minutes) of the main fire, based on mass fuel loss rate in this case. However, the fires would have certainly been under control within a few more minutes at this rate of flow. This is the principle of CFR working at its very limits. However, the CFR is likely to be much higher for 'real' fires where fire loading increases beyond simple 'wooden' fuels. The true CFR in an apartment fire could be said to be at least *double* that estimated by Sardqvist for ordinary wooden fuels and 0.04kg/m2 per second might be a more reliable estimate. This equates to a *minimum* firefighting flow-rate of 240lpm when operating in the *direct attack* mode against a 100m2 fire. Interestingly, Stolp (1976)(15) suggested the CFR (minimum flow) for a 100m2 compartment fire was around 200lpm.

So what exactly is the *optimum* flow-rate for structural firefighting that Sardqvist refers to in his research, where the CFR is adequately surpassed whilst still providing the smallest total water mass for extinction? A study by Rasbash (1985) on diffusion flames indicated that the removal of between 30-35% of the heat-release energy of a diffusion flame is generally sufficient to extinguish the fire.

Sardqvist's research (1998)(16) into actual flows used at 307 selected fires in non-residential buildings in London, UK suggested that most working fires were extinguished with a maximum 600lpm flow-rate, and that 75 percent of fires did not increase in size following fire brigade arrival. His studies also revealed that only a very small percentage of structural fires (in the study) exceeded 100m2, requiring less than 30 firefighters to deal with the majority of incidents. It should be noted here that the author believes Sardqvist's final conclusions on flow-rate were substantially over-estimated due to a reliance on SRDB (Home Office Scientific Research & Development Branch) nozzle flow figures used in his research. These SRDB codes were never meant to represent actual practical fire-ground flow-rate capabilities. For example, the code used for main-line branches (mostly 45mm but some 70mm hose-lines) suggested a flow-rate of 870lpm. In reality, the flow factors and excessive nozzle reaction forces associated with such flows through 12.5mm; 19mm and 25mm nozzles (as used at the time SRDB codes were created) would have prevented such high flows from ever being achieved on the fire-ground, except in the minority of exterior defensive situations. A similar study in New Zealand, by Beever & Davy (17) suggested that 87 percent of 290 working structural fires were extinguished using a flow of 600lpm or less. Only 3 percent of structural fires required larger flows in the same study. In 1999 Peterson suggested that research (13) in the USA had led him to conclude that fire departments have only a 50% chance of preventing total compartment or building loss once the fire size reaches 86m2.

Parameter	Mean	St. dev.	Cases
Time Preheating - Ignition [min]	44.9	118.3	50
Time Ignition - Discovery [min]	9.1	15.0	116
Time Discovery - Arrival [min]	8.4	13.0	271
Time Arrival - Intervention [min]	2.0	2.8	153
Time Intervention - Spread stopped [min]	7.4	25.1	152
Time Spread stopped - Flames out [min]	13.3	87.8	238
Time Flames out - Fire dead [min]	40.3	203.5	236
Area when first discovered [m²]	3.2	7.3	269
Area when first f/f arrived [m²]	10.0	47.3	299
Final area of fire spread [m²]	24.0	113.4	300

Table 5 - The mean and standard deviation of parameters, and the number of fires on which they are based, from the 307-fire study in London – *Real Fire Data, London 1994-1997, Stefan Sardqvist 1998 Report 7003 Lund University Sweden*

It has been suggested that fire brigades may, on occasions; use up to 100 times more water than is required theoretically. As large fires are of particular concern, the correlations x-x and y-y from research data displayed in figure 7 (below) are of relevance, where it can be seen that 'real' firefighting flow-rates, at large structure fires in the 1950s and 1960s, were in excess of 1,700lpm in compartments or spaces around 93m2.

If we consider the difference between an offensive and a defensive operation, it may well be that the largest fires are not extinguished by an *offensive* operation, but rather through a *defensive* approach. This leads to a much lower water demand. There may be cases where the fire is simply retained within its boundaries and runs out of fuel after a couple of hours.

In 1990, as a London Fire Brigade Fire Investigator, I undertook extensive research into flow-rates (6) at 120 working fires in London and the USA and noted that many large fires were being suppressed during their *decay-phase* on the fire development gradient. This was particularly evident in a series of several working high-rise fires I had researched during the 1980s-1990s in the USA and UK, where flows around 113-190lpm per 100m2 of involved floor-space were all that was available to tackle several floors of fire! The fires were extinguished but not without some amazing efforts. The fire floors themselves appeared to have consumed most of the available fuel and final extinction was generally achieved during the decay-phase, (i.e.; the CFR during development had not been met) whilst directing major efforts at reducing further spread to the floors above. My research also suggested that similar flows (113-380lpm per 100m2) had been used (often successfully on the *fire 'growth'* side of the gradient) to suppress 100 working fires that occurred in London during a six-week period in 1990. This data would conform to other research that followed (Barnett 1994) and might suggest the crossover between extinction in the decay-phase, as opposed to the growth-phase, almost certainly exists somewhere between 226-380lpm per 100m2 of fire involvement. The *optimum* flow-rate Sardqvist refers to is probably located somewhere within the same parameters.

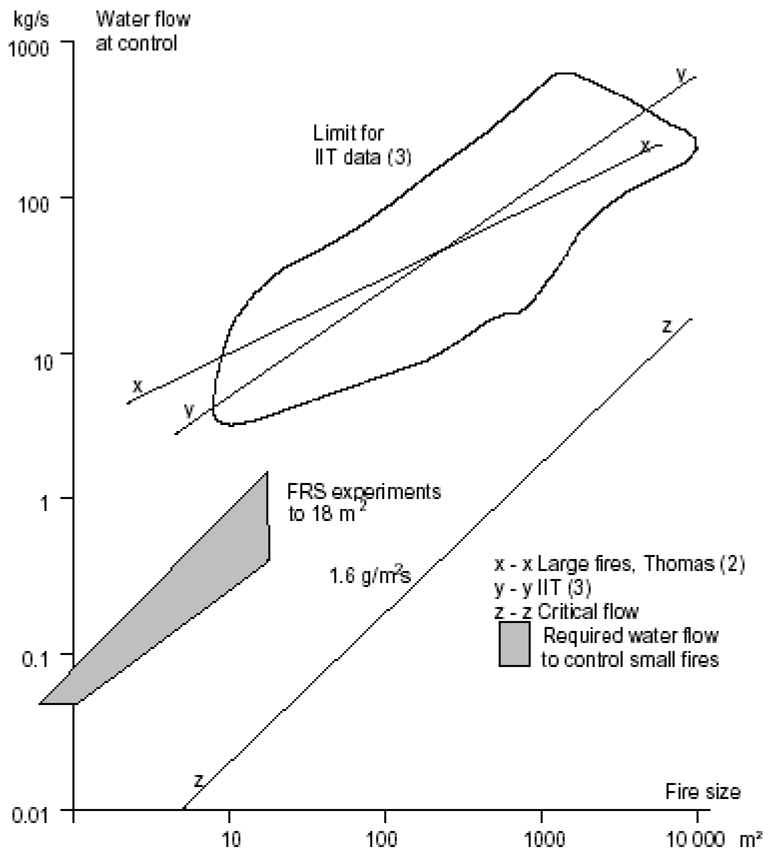

Fig.7 The actual used water flow in relation to the area of the fire is shown. The data are derived from real fires, and taken from reports published in the late 1950's and 1960's. These may not be wholly reliable after forty years – *An Engineering Approach to Firefighting Tactics, Stefan Sardqvist 1996, Report 1014 Lund University Sweden*

As a technical author and serving firefighter, I campaigned tirelessly for years where flow-rates (in the UK) were becoming dangerously low, by intention, as CFBT instructors became highly influenced through fighting hundreds of training fires during the *gaseous-phase* of 'container' burns. This experience in a 'controlled' environment resulted in a team of instructors working with a nozzle manufacturer to produce a nozzle offering flow-rates of 40 and 90lpm. Such flows are ideally suited to the restricted amounts of *gaseous-phase combustion* (1.5MW) that may be regularly encountered inside CFBT flashover simulators but are far from capable in dealing with 'real-world' compartment fires that are progressing towards and beyond flashover. However, this nozzle has set a worrying standard for 19mm initial attack high-pressure hose-reels and is now (2005) widely used on real structure fires, where reports of difficulties in fire suppression efforts are becoming commonplace!

Specific Heat (18)

Specific heat is the amount of heat required to raise 1 gram (g) of a substance by 1 degree Celsius (°C). Specific heat is expressed in Joules (J). The specific heat capacity of water varies slightly from 0°C to 100°C, but at 18°C it is 4.183 kJ/kg°C. 18°C is selected here because it is the typical temperature of water when it comes from an underground water main.

<u>Example 1</u>
Determine how much heat will be absorbed in raising 10 kg of water from 18°C to 100°C.

= 4.183 kJ/kg°C x 10 kg x (100°C - 18°C) = 3,430 kJ

Specific heat capacity is expressed in J/kg.K or J/kg.C.

Latent Heat of Vaporisation (18)

The latent heat of vaporisation is the amount of heat required to change a liquid into a vapour without a change in temperature. For water, this is 2,257 kJ/kg.

Water does not boil immediately upon reaching its boiling temperature (100°C at sea level). Once boiling point is reached, the water must absorb additional heat energy to convert the water into a vapour. This is the latent heat of vaporisation. Of the unique properties of water, this one is the most valuable as a fire protection tool.

<u>Example 2</u>
Determine how much heat will be absorbed if 1 kg of water at an initial temperature of 18°C is perfectly converted to steam at 100°C -

= 4.183 kJ/kg x (1 kg) x (100°C - 18°C) + 2,257 kJ/kg x (1 kg)
= 343 kJ + 2,257 kJ
= 2,600 kJ
= <u>2.6 MJ</u>

Combined Specific Heat & Latent Heat (18)

The final effect of water upon a fire is a combination of specific heat and latent heat of vaporisation. We have to compute the total amount of heat absorbed by a unit of water when raised from its initial temperature in a water main to the temperature of the fire gases. The total heat absorbed occurs in three stages -

(a) Specific heat multiplied by the mass of water and the increase in temperature to reach boiling temperature at 100°C;
(b) Plus, the product of latent heat of vaporisation at 100°C multiplied by the weight of water;
(c) Plus, the specific heat of steam multiplied by the mass of steam and the increase in temperature from 100°C to the temperature of the fire gas.

Example 3

Determine how much heat will be absorbed if 1 kg of water at 18°C is perfectly converted to water vapour at 300°C

= *4.183 kJ/kg x (1 kg) x (100°C - 18°C) + 2,257 kJ/kg x (1 kg) + 4.090 kJ/kg x (1 kg) x (300°C - 100°C)*
= *343 kJ + 2,257 kJ + 818 kJ*
= *3.418 kJ*
= *3.4 MJ*

This is illustrated graphically in Fig. 8.

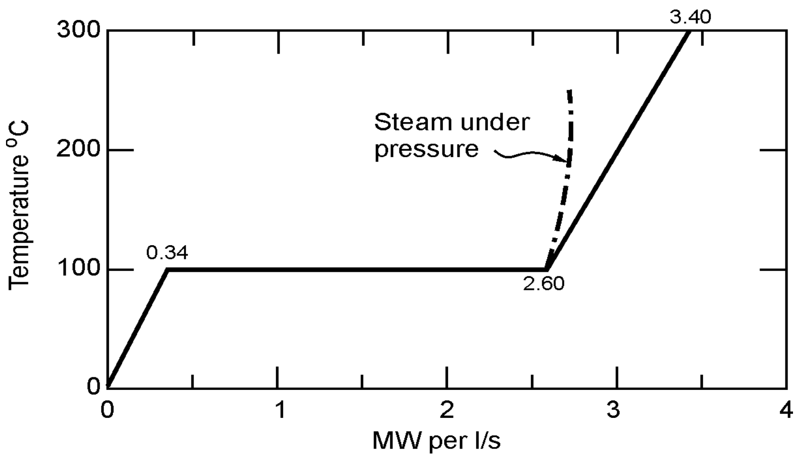

Figure 8 - Cooling power of water at 18°C applied to a fire at the rate of 1kg/s

The information in Table 6 below indicates that 1 kg of water, converted to steam as in Example 3 above, would be an insufficient amount to absorb the heat released by 1 kg of any of the fuels listed. The result however is different when water is applied to a fire in typical fire fighting rates in kilograms per second, that is, litres per second.

Substance	MJ/kg
Wood	16
Polyurethane	23
Coal	29
Rubber Tyres	32
Petrol	45

Table 6. Net Heat of Combustion values for selected common fuels.

In example 2 above we determined that 1 kg of water when boiled at 100°C from an initial temperature of 18°C can absorb 2.6 MJ. Put another way, for each MJ of fuel in the fire load a firefighter theoretically needs 0.38 kg of water as steam at 100°C to absorb the heat output of each MJ in the fuel.

As a further example, each kg/s of water vapour at 300°C fed into a fire is theoretically capable of absorbing 3.4 MW of fire intensity as shown in Fig. 8 above.

From this it will be apparent that 5 kg of water, as water vapour at 300°C, has the theoretical capacity to absorb 5 x 3.4 = 17 MJ. This is more than enough to absorb the heat generated by 1 kg of wood or 16 MJ when consumed in a fire. It will also be apparent that 14 kg of water has the capacity to absorb the heat generated by 1 kg of burning petrol.

Efficiency in Fires (18)

Water can never be applied at 100% efficiency for various reasons, and most building fires do not retain 100% of the heat energy in the room where the fire is occurring. The net result is that both the energy absorption of the water and the energy production of the fire need to be modified by calculated efficiency factors.

These can be expressed as -

(a) heat absorption efficiency of a fire hose;
(b) heat production efficiency of a compartment fire.

Heat Absorption Efficiency of a Fire Stream (18)

The heat absorption described so far illustrates perfect conditions for the absorption of heat by the water. A tactical water application directly into the fire rarely approaches 100% efficiency in most cases. Unlike a laboratory test, there will always be inefficiencies and variables in the application of water to a compartment fire. Water may also be used to cool down fire gases and hot surfaces to enable a firefighter to approach closer to the actual fire source itself to complete suppression. Parts of the fire may have to be extinguished first to enable the firefighter to reposition to carry out the extinction of other parts of the fire. In some situations, as little as 20% of the water flow may actually reach the burning fuel surface.

There have been several attempts to estimate reliable *efficiency factors* for firefighting streams, often based on extrapolated data from theoretical computer models. However in general, the most accurate of all these efficiency factors are those that result following pain-staking research covering many hundreds of real fires. Previous research has indicated that to overwhelm a fire, the efficiency of water as a cooling medium is about one-third, or 0.32. Thus it was proposed then that the effective cooling capacity of a flow of 1 l/s is 0.84 MW, or a standard 10 l/s fire hose is 8.4 MW, demonstrating a practical cooling capability with 33% efficiency. However, more recent research based on extensive real fire data suggests a 33% factor maybe somewhat under-estimated. A figure of three quarters (75% efficient) appears more reliable for a fog pattern and one-half (50% efficient) for a solid-bore stream. The cooling power of each kg (litre) of water per second applied to a fire increases with temperature. Therefore the selection of an effective cooling power of only 0.84 MW (100deg.C) may be seen as somewhat conservative. At 400deg.C the cooling power can be seen to be closer to 1 MW and at 600deg.C it is close to 1.2 MW (see Fig.8).

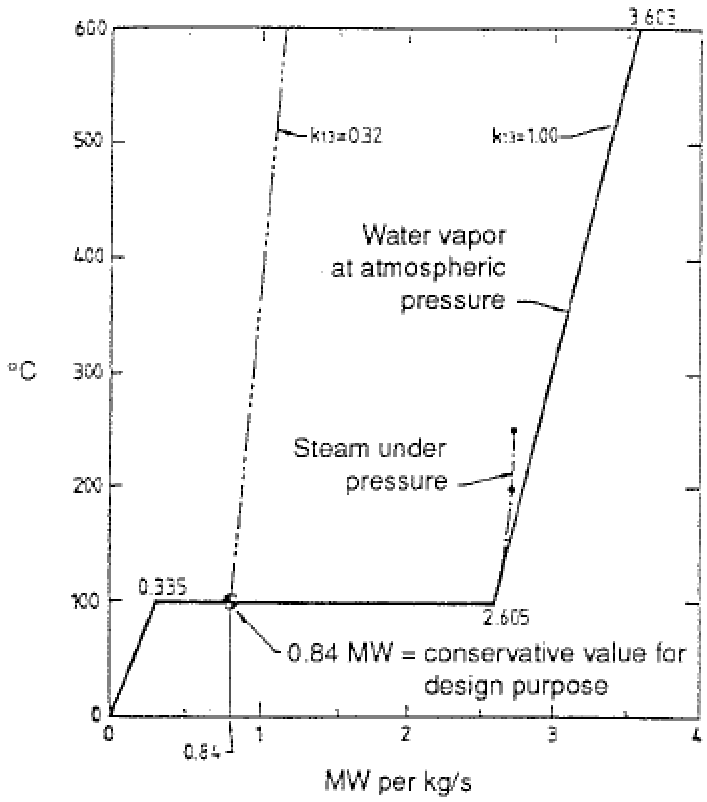

Figure 9 - Cooling power of water applied to a fire at the rate of 1 kg/s (1 litre/s)

In combining Cliff Barnett's SFPE NZ engineering research with my original fire-flow calculations based on real fire data, the updated *efficiency factors* are inserted into Barnett's flow-rate calculations as follows -

Example 4

Find the total heat energy absorbed (Q_s) by a 7 kg/s jet nozzle if the water is initially at 18°C, assuming that perfect steam conversion is accomplished at 100°C

Q_s = 7 kg/s x 2.6 MJ/kg x 1.00 = 18.2 MW

Example 5

If the efficiency of a fog nozzle delivery at 7 kg/s is only 75%, find the total heat energy absorbed.

Q_s = 7 kg/s x 2.6 MJ/kg x 0.75 = 13.6 MW

Example 6
If the efficiency of a jet nozzle delivery at 7 kg/s is only 50%, find the total heat energy absorbed.

$$Q_s = 7 \text{ kg/s} \times 2.6 \text{ MJ/kg} \times 0.50 = \underline{9.1 \text{ MW}}$$

Example 7
An office type of fire burning at 100% efficiency would have an average release heat rate of approximately 0.25 MW for each square metre of area. Determining the amount of heat released for this fire in a space measuring 6 m x 6 m, we find:

$$6 \text{ m} \times 6 \text{ m} \times 0.25 \text{ MW/m}^2 = 9.0 \underline{\text{ MW}}$$

If the foregoing is true, one hose-line delivering 7 kg/s in a fog pattern at 75% efficiency or a solid-bore jet stream at 50% efficiency could both deliver enough water flow to control and extinguish this *fire burning at 100% efficiency* (See Examples 5 and 6 above).

Complex computer models have been developed to provide theoretical water flow estimations and are formatted to take into account additional factors, such as firefighting team intervention times; the effect of automatic suppression systems that may have operated, correcting HRR as necessary; ventilation parameters directly affecting HRR; thermal radiation and specific boundary cooling demands, thereby balancing total water requirements for a range of fires in a structural setting.

Heat Production Efficiency of a Compartment Fire

Combustion, or burning, consists in causing chemical reactions that generate heat to take place between the oxygen (generally supplied as air) and the combustible material (generally hydrogen or carbon or hydro-carbon compounds of these elements). Combustion of hydrocarbon fuel is brought about by the combustion of the hydrogen (H) and carbon (C) in the fuel with the oxygen (O) contained in the air (and/or in the fuel). Depending on ventilation parameters and other factors, the *burning efficiency* of an enclosed fuel load (within a compartment with limited openings) is never able to achieve 100 percent. Where compartmental ventilation openings are limited, a fire will take longer to consume any particular fuel-load than it would if it were burning in the open air.

Combining Efficiencies of Fire Streams with Compartment Fire Burning Rates (18)

The alteration of *firefighting stream (cooling) efficiency factors* by Barnett, inline with Grimwood's flow-rate research, coupled with the burning efficiency of a compartment fire (taken as 50 percent), led to an updated approach by Barnett in TP 2004/1 (example) -

> <u>*Example 8*</u>
> *If the efficiency of a jet nozzle at 7 kg/s is 50%, as in Example 6, but the efficiency of the fire is only 50%, find the total energy that can be absorbed by the water flow.*
>
> $$Q_s = 7 \text{ kg/s} \times (0.50 \times 2.6 \text{ MJ/kg}) / 0.50 = \underline{18.2 \text{ MW}}$$
>
> *Or by re-arranging the equation the amount of water required will be*
>
> $$F = (0.50 \times 18.2 \text{ MW}) / (0.50 \times 2.6 \text{ MJ/kg}) = \underline{7 \text{ kg/s}}$$
>
> *where,* F = *firefighting water flow in kg/s (litres/second)*
> Q_s = *heat absorption capacity of fire stream*

In practical terms it must be pointed out that a firefighter's physiological barriers are relative to compartment size where, for example, a 1MW fire enclosed within a 40m3 compartment may present similar barriers to the firefighter as a 16MW fire in a larger 300m3 compartment.

The reliability of this method is somewhat dependent on the accuracy of the heat release rate data and cooling efficiency value used, which in this case is based on real fire data obtained from structural enclosures. This method considers not only the heat absorbing properties of water from a scientific viewpoint but also the efficiency of firefighting streams when used to control actual enclosure fires, exhibiting post flashover conditions, demonstrating similar HRR to common compartment fires.

Tactical Flow-Rate (TFR) & Fire-ground Formula

The author's original research (6) from the 100-fire study in London (1989) produced a range of flow-rates that were used by firefighters to suppress serious working fires in a wide range of occupancies. My estimates suggested that flow-rates between 200-400 lpm were generally successful in suppressing developing compartment fires up to 100m2, although lower flow-rates were sometimes resulting in post-flashover fire suppression during the *decay stages* of fire development.

My continued interest in this area of research, based on further detailed analysis of empirical data, resulted in a reliable fire-ground calculation –

A x 4 = lpm (Grimwood 1999)

Where A = area of fire involvement in m2

This suggests that 100m2 of fire involvement would require 400lpm to deal effectively, during the growth side of the fire development gradient. It was further proposed that this formula was based upon on average office fire loads and that where higher fire loads, or structural elements were to become involved in the fire, the baseline flow-rate should be increased by 50 percent (A x 6 = lpm).

Cliff Barnett's research (18) for the SFPE NZ took account of this approach and applied the FLEDS (Fire Load Energy Densities) test to my own fire-ground formula to compare how close it was to his own research. Amazingly, the two different research approaches compared so well that he decided to combine the two, one based on detailed scientific theory with the other based very much on empirical data derived from a large quota of 'working' inner city and suburban fires. My recorded flow-rates of 200, 400 (office fire loads) and 600 lpm as derived from the 100-fire study were well placed within the NZ FLEDS system at 400, 800 and 1,220 MJ/m2 respectively. This provided the impetus for updating in relation to accepted fire stream efficiency factors as discussed earlier.

There are many correlations between the tactical flow-rate (Grimwood) and other fire-ground formulae as developed elsewhere. If we refer to the 100m2 compartment then the NFA linear formula would suggest 1350lpm might be needed to fully extinguish the fire - using the NFA linear equation – NFF = (L x W) / 3 (*NFF – 'Needed Fire Flow' is an ISO term)*. One might consider an over-estimate in the NFA formula now becomes apparent. However it should be remembered that the NFA method of estimating requirements has a fire flow *safety factor* designed into the calculation and further applies to structures that are being purposely 'opened up' to allow venting of the combustion products, naturally leading to greater heat release rates. It is also limited by percent of fire involvement – i.e.; the NFA (linear) formula is designed to function within certain parameters. The formula (area ft2 / 3) is designed for fire-ground use in aggressive interior fire operations and is in an abbreviated format of the original formula, simplified for fire-ground use. It is reported by Chiefs Burns & Phelps that that the NFA method of calculating NFF is based upon an interior aggressive fire attack and that the formula may become increasingly inaccurate where fire involvement percentages above 50% of large floor spaces might not offer any opportunity for such an approach. The accuracy of the NFA formula may therefore be questionable in compartments larger than 560m2, demonstrating in excess of 50% fire involvement. The NFA approach to fire-ground flow-rate calculation is designed upon direct attack (*fuel surface*) applications in commercial structures, where the upper flow-rate does not exceed 3,780lpm and the property is not over-sized. It is acknowledged by those who produced the formula, in its revised format, that the NFA calculation provides more water for suppression than would be necessary if the building were to remain un-vented and tightly closed. It is also worth noting that the recommended flow-rates resulting from the NFA formula takes into account *both attack and support* (back-up) hose-lines as if they are discharging their full flow capability together.

Similarly, the IOWA flow-rate research, which dates back to the 1950s, was closely matched to the author's *tactical flow-rate* and an attempt at combining the two approaches was made by John Wiseman in 2003.

Tactical Flow-rates and baseline flows for Interior Attack Hose-lines

The Lund research (above) demonstrated that flow-rates of 113lpm were unable to control developing compartment fires within the six-minute control criteria and that any such control achieved after this time would have been during the *decay-phase* of the fires progression. The same research demonstrated a flow-rate of 226lpm was able to achieve extinction during the *growth phase* of the fire's development. We have also seen much empirical data from different sources that suggest the vast majority of working structural fires are smaller than 100m2 and are suppressed with a flow-rate below 600lpm. The author's own research in 1989 suggested flow-rates between 200-400lpm was generally successful in suppressing *developing* compartment fires up to 100m2 and Stolp suggests 200lpm will suffice. Therefore, the author proposes a minimum tactical flow-rate (TFR) of 400lpm per 100m2 of compartmental fire involvement *for attacks on both the fuel and gaseous phases of combustion* and this includes a small margin for error. If the fire has spread to a stage where it involves actual *structural* members, the baseline flow-rate should be increased by at least 50 percent (600lpm per 100m2). In terms of tackling compartment fires in the gaseous phase, it should be mentioned that, in the author's experience, the strategy of 3D water-fog attack is limited to a maximum compartment size of 70m2.

There have been several international research studies (19) into the ideal *base-line flow* for a primary low-pressure attack hose-line and these have been fairly consistent in their approval for the 51mm hose-line flowing 450-560lpm. This research takes into account such relevant issues as (a) optimal flow-rate; (b) manoeuvrability and manual handling; (c) nozzle reaction; and (d) stowage and tactical deployment issues. Such hose-lines are fast becoming established as the ideal attack tools, for a primary *offensive* advancement by two firefighters into most compartment/structural fires where the fire area is contained within 100m2. In situations where a defensive mode of attack is necessary, or where any particular fire front is rapidly escalating through an established heavy fire loading, extensive structural fire involvement, or wind gusts (for example), then higher flows will be necessary. However, be aware that flows up to 950lpm from a 51mm hose-line are generally perfectly manageable by a team of two firefighters in a *defensive or offensive* 'holding position' (i.e.; the nozzle reaction would be too powerful to *advance* such a line whilst flowing).

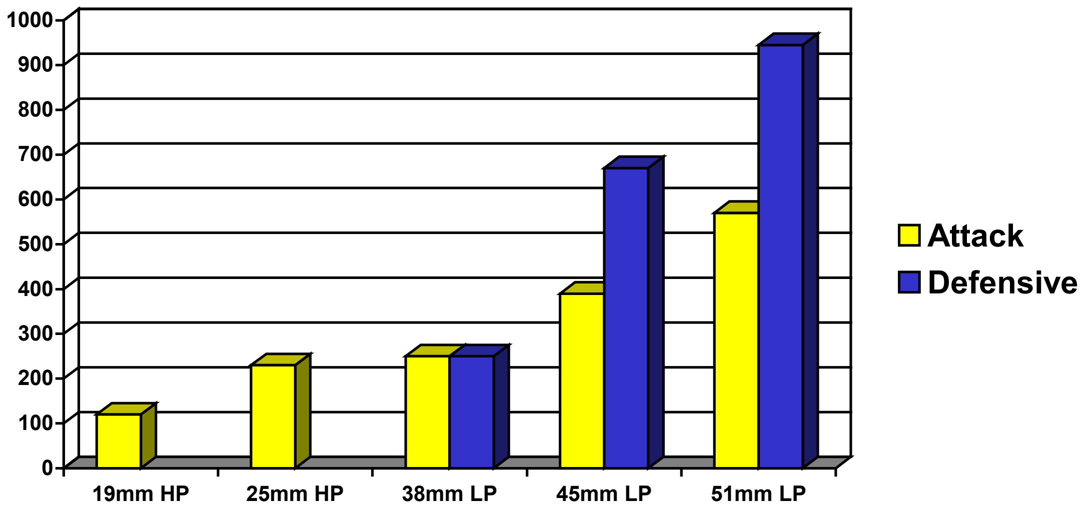

Figure 10 – Flow-comparisons from a range of hose options.

Taking into account all the available scientific research, computer modelling and empirical studies aimed at finding the safest and most effective flow-rates for the various methods of interior fire attack, the author suggests that, after the primary option of a 25mm HP rapid attack hose-reel, a 51mm hose-line, coupled with a suitable 450lpm or 560lpm combination straight-stream/spray nozzle, is undoubtedly the most *versatile* option for dealing with both fuel-surface and gaseous-phase compartment fires. In a direct attack the combination nozzle's straight stream flowing 450lpm at 7 bars nozzle pressure (NP) will produce a nozzle reaction force (NR) of 268 Newtons, or 333N for a 560lpm flow, which are both within acceptable limits that will allow a two-person crew to *advance* the line safely and easily. Any increase above 333 Newtons (N) NR will make it difficult for a two-person crew to move a flowing attack line although a three-person crew should be able to handle and advance a hose-line demonstrating a 422N NR.

One Firefighter	266 Newtons
Two Firefighters	333 Newtons
Three Firefighters	422 Newtons

Table 7 – Maximum acceptable Nozzle Reaction forces (6) (Newtons) that would enable a crew to advance a flowing hose-line from a static position (0.22563 x LPM x Square root of NP (Bars) – Jet/fog Combination Nozzle) The amount of NR that a single firefighter can handle on a static hose-line operating in fog mode is considerably more.

In any situation involving attack-line advancement into 100m2 of fire involvement, the placement of an early 'back-up' line is always an important *secondary action* during the initial response.

Firefighting in Large Compartments

In practical terms, a fully involved 100m2 open-plan structure fire can be dealt with most effectively using a high-flow attack hose-line from the exterior. The greater the flow the sooner the fire will darken. A direct attack utilizing a straight-stream or smoothbore nozzle will suffice. The recommended minimum *tactical flow* (400lpm) should overcome the fire-front even as the fire is developing. If the fire has spread to involve structural components; walls; beams; floors; roofs, breaching compartmental boundaries etc, the higher flow of 600gpm may be needed. Where structural involvement is 100 percent then high-flow blitz lines and firefighting monitors may well be required. An application of 3D offensive water-fog is not the optimum approach for a fire of these dimensions unless the structure is compartmented or the fuel source is shielded.

Firefighting in Small Compartments

It is important to recognize the limitations of the fire-ground formula as derived by the author. When applied to small compartments, such as a 4m x 4m room demonstrating a fully involved 10MW fire, a calculated flow-rate would demand a minimum flow of –

F = (0.50 x 10 MW) / (0.50 x 2.6 MJ/kg) = 3.84 kg/s

Which is an actual flow of 230lpm. Such a fire would be within the capability of a 25mm HP hose-reel or a larger 51mm low-pressure attack hose-line.

However, by applying the fire-ground formula A x 4 to this situation would produce an under estimate of requirements –

F = A (16m2) x 4 = 64 lpm

Therefore, the limitations of this fire-ground method of estimating needed flow-rate lie between floor spaces of 50m2 and 600m2 based on 2.5m high ceilings.

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