Fire Suppression Calculations

There are currently four basic methods of fire suppression that are currently used by fire-fighters to gain control and suppress fires in compartments, enclosures or structures. Each particular method offers distinct advantages and disadvantages over each other in specific scenarios. There is no single method that stands out from another as the optimum method for general all-purpose use although 'direct' fire fighting, using straight streams, is the most widely used and readily available approach.

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Four methods of gaining control or achieving suppression of a compartment fire -

1. ***3D Fire-fighting (short burst water-fog – gaseous phase fire)***
2. ***Indirect Fire-fighting (long burst water-fog – gaseous phase fire)***
3. ***Direct Fire-fighting (straight stream – fuel phase fire)***
4. ***Water Additives & Enhancements (fuel phase fire and thermal reduction)***

Each particular method of fire control utilises various mechanisms of fire suppression -

1. ***Fuel (fuel-phase) cooling***
2. ***Flame (gas-phase) cooling***
3. ***Flame (gas-phase) inerting (Oxygen Displacement)***
4. ***Decreasing thermal radiation***
5. ***Diluting flammable vapour/air mixture(with water-vapour)***
6. ***Chemical Inhibition***

3D	*2. Gas-phase Cooling* *5. Dilution of flammable gas layer*
INDIRECT	*3. Gas-phase Inerting (Oxygen Displacement)* *2. Gas-phase Cooling* *5. Dilution of flammable gas layer*
DIRECT	*1. Fuel-phase Cooling*
CAFS & CLASS 'A'	*1. Fuel-phase Cooling* *4. Decrease Thermal Radiation*

1. 3D Fire-fighting - To achieve effective results the 'fog-cone' and application angles are as important as the practical aspects of nozzle 'pulsing'. For example, a 60-degree fog-cone applied at a 45-degree angle to the floor into an average room (say 50 m^3) will contain about 16 m^3 of water droplets. A one second spurt from a 100 LPM flow hose-line will place approximately 1.6 litres of water into the cone.

For the purposes of this explanation let us suggest a single 'unit' of air heated at 538°C weighs 0.45kg and occupies a volume of one cubic metre. This single 'unit' of air is capable of evaporating 0.1kg (0.1 litre) of water, which as steam (generated at this, a typical fire temperature in a compartment bordering on flashover) will occupy 0.37 m^3.

It should be noted that a 60-degree fog-cone, when applied, would occupy the space of 16 'units' of air at 538°C. This means that 1.6kg (16 x 0.1kg), or 1.6 litres of water can be evaporated - ie; the exact amount that is discharged into the cone during a single one second burst. This amount is evaporated in the gases before it reaches the walls and ceiling, maximising the cooling effect in the overhead. It may be seen that too much water will pass through the gases to evaporate into undesirable amounts of steam as it reaches the hot surfaces within the compartment.

Now, by resorting to Charles Law calculations we are able to observe how the gases have been effectively cooled, causing them to contract. Each 'unit' of air within the cone has now been cooled to about 100°C and occupies a volume of only 0.45 m^3. This causes a reduction of total air volume (within the confines of the cone's space) from 16 m^3 to 7.2 m^3. However, to this we must add the 5.92 m^3 of water vapour (16 x 0.37) as generated at 538°C within the gases. The dramatic effect has created a negative pressure within the compartment by reducing overall volume from 50 m^3 to 47.1 m^3 with a single burst of fog! Any air inflow that may have taken place at the nozzle will be minimal (around 0.9 m^3) and the negative pressure is maintained.

Paul Grimwood
Fog Attack 1991
www.firetactics.com

2. Indirect Fire-fighting - *Giselsson and Rosander present a calculation to explain the action of indirect firefighting attack (the application of water to hot surfaces to create a steam rich atmosphere, displacing oxygen, and controlling a fire), this has been taken up by Grimwood, with a few corrections in his book 'Fog Attack'. The explanation needs some embellishment to aid understanding due to a lack of rigour in the original (for example a statement such as 90° =380kW is nonsensical). In addition some steps in the calculation and associated values are missing. This is an attempt to rewrite the indirect fog attack example calculation clearly.*

A REVISED CALCULATION

Consider a room with a 40m^2 floor area, 2.5m high filled with burning gases. Application of water is intended to create an atmosphere of 10% water vapour at 180°C (supply water at 10°C).

Volume of steam at 180°C = 10 m^3 (10% of 100m^3)

Using the ideal gas laws to correct this volume to a temperature of 100° C

$V_{100} = V_{180}(100+273)/(180+273) = 0.823\ V_{180} = 8.23\ m^3$

This is 8230 litres of steam at 100°C

A litre of water will vaporise to 1700 litres of steam at 100°C. To create the 10% steam atmosphere

8230/1700 = 4.84 litres of water must be vaporised.

To heat 4.84 litres of water from 10°C to steam at 180°C energy must be provided to:

raise the water temperature from 10° to 100°C

provided latent heat of vaporisation

raise steam temperature from 100°C to 180°C

Generally

$E = m\ (C_{p(water)}Dq_w+L+C_{p(steam)}Dq_s)$

where m	Mass of water (kg)
$C_{p(water)}$	Specific heat capacity of water (J/kg/K)
Dq_w	Temperature rise of the water (K)
L	Latent heat of water (J/kg)
$C_{p\ (steam)}$	Specific heat capacity of steam (J/kg/K)
Dq_s	Temperature rise of the steam (K)

NB. the mass of 1 litre of water is 1kg

Evaluating gives

$E = 4.84\ (4180*90 + 2260000 + 2020*80) = 13.541\ MJ$

Giselsson and Rosander assume that in the first instance all this heat is held in the first 1mm of the wall. The available energy in this slab of wall may be found from:

$$E_{wall} = p_{wall}Adc_{pwall}Dq_w \text{ Joules}$$

Where p_{wall} Density of the wall material

A	Area of wall/ceiling
d	Depth

$C_{p(wall)}$ Specific heat capacity of the wall material

Dq_w Temperature change of the wall

Assuming an initial wall temperature of 500°C and final temperature of 180°C, density of 1000 kg/m^3 specific heat capacity of 1000 J/kg/K and the depth of 1mm then the area required to provided the required amount of heat is:

$$A= \left(\frac{E_{wall}}{\rho_{wall} C_{pwall}\, d\Delta\theta_w}\right) = \left(\frac{13.5\ x106}{1000.0x1000.0x0.001x\ (500.0-180.0)}\right)$$

= 42.2 m^2

Therefore 4.9 litre of water should be applied to $42.0^2$of wall to achieve the required concentration of steam, an application of 0.11 litre/m^2 as calculated by Giselsson and Rosander and reproduced by Grimwood.

A transient model for heat losses from the walls could significantly improve this analysis as the reheating time and hence the time between applications and the duration of subsequent applications of the spray could be estimated.

Several fire suppression/control actions have occurred, firstly as stated by Giselsson and Rosander the oxygen concentration in the room is reduced inhibiting combustion reactions. In addition the compartment temperature will have been reduced decreasing thermal feedback to the fuel surface and the heat losses to the boundary increased. These thermal factors may be sufficient for the fire to jump to a lower stable equilibrium (a reverse of the flashover mechanism).

Giselsson and Rosander continue to warn of the effects of over drenching (causing the wall temperature to fall below 100°C) and observing that fuel rich atmospheres will require less water since they will be oxygen depleted already and leaner mixtures will require more. It is then stated that the opening should be kept as small as possible during the fire fighting procedure, presumably to reduce incoming oxygen. The reignition hazard is emphasised.

Richard Chitty
A Survey of Backdraught
FRDG-UK-ODPM-5/94

Reconnaissance and reading the fire

The first step of the operations is a reconnaissance to search for the origin of the fire (which may not not be obvious for an indoor fire, especially when there are no witnesses), and spot the specific risks and the possible casualties. Any fire occurring outside may not require reconnaissance; on the other hand, a fire in a cellar or an underground car park with only a few centimeters of visibility may require a long reconnaissance to spot the seat of the fire.

The "reading" of the fire is the analysis by the firefighters of the forewarnings of a thermal accident (flashover, backdraft, smoke explosion), which is performed during the reconnaissance and the fire suppression maneuvers. The main signs are:

- hot zones, which can be detected with a gloved hand, especially by touching a door before opening it;
- the presence of soot on the windows, which usually means that combustion is incomplete and thus there is a lack of air
- smoke goes in and out from the door frame, as if the fire breathes, which usually means a lack of air to support combustion;
- spraying water on the ceiling with a short pulse of a diffused spray (e.g. cone with an opening angle of 60°) to test the heat of the smoke;
    - when the temperature is moderate, the water falls down in drops with a sound of rain;
    - when the temperature is high, it vaporises with a hiss.

Use of water

Often, the main way to extinguish a fire is to spray with water. The water has two roles:

- in contact with the fire, it vaporizes, and this vapour displaces the oxygen (the volume of water vapour is 1,700 times greater than liquid water); the fire has no combustive agent anymore;
- the vaporization of water absorbs the heat; it cools the smoke, air, walls, objects, etc. and prevents an extension of the fire.

The extinction is thus a combination of "asphyxia" and cooling. The flame itself is suppressed by asphyxia, but the cooling is the most important element to master a fire in a closed area.

Closed volume fire

The use of constant flow water-fog can have unfortunate and dramatic consequences: the water pushes air in front of it, so the fire is supplied with extra oxygen before the water reaches it. This activation of the fire, and the mixing of the gases produced by the water flow, can create a flashover.

The most important issue is not the flames, but control of the fire, i.e. the cooling of the smoke that can spread and start distant fires, and that endanger the life of people, including firefighters. The volume must be cooled before the seat is treated. This strategy, originally of Swedish origin (Mats Rosander & Krister Giselsson), was further adapted by London Fire Officer Paul Grimwood following a decade of operational use in London's busy west-end district between 1984-94 (www.firetactics.com) and termed three-dimensional attack, or **3D attack**.

Use of a diffused spray was first proposed by Chief Lloyd Layman of Parkersburg, West Virginia Fire Department, at the Fire Department Instructor's Conference (FDIC) in 1950 held in Memphis, Tennessee, U.S.A.

Using Grimwood's modified '3D attack strategy' the ceiling is first sprayed with short pulses of a diffused spray:

- it cools the smoke, thus the smoke is less likely to start a fire when it moves away;
- the pressure of the gas drops when it cools (law of ideal gases), thus it also reduces the mobility of the smoke and avoids a "backfire" of water vapour;
- it creates an inert "water vapour sky" which prevents *roll-over* (rolls of flames on the ceiling created by the burning of hot gases).

Only short pulses of water must be sprayed, otherwise the spraying modifies the equilibrium, and the gases mix instead of remaining stratified: the hot gases (initially at the ceiling) move around the room and the temperature rises at the ground, which is dangerous for firefighters. An alternative is to cool all the atmosphere by spraying the whole atmosphere as if drawing letters in the air ("pencilling").

Calculation of the amount of water required to suppress a fire in a closed volume (Compartment)

From Wikipedia - In the case of a closed volume, it is easy to compute the amount of water needed. The oxygen (O_2) in air (21%) is necessary for combustion. Whatever the amount of fuel available (wood, paper, cloth), combustion will stop when the air becomes "thin", i.e. when it contains less than 15% oxygen. If additional air cannot enter, we can calculate:

- The amount of water required to make the atmosphere inert, i.e. to prevent the pyrolysis gases to burn; this is the "volume computation";
- The amount of water required to cool the smoke, the atmosphere; this is the "thermal computation".

These computations are only valid when considering a diffused spray which penetrates the entire volume; this is not possible in the case of a high ceiling: the spray is short and does not reach the upper layers of air. Consequently the computations are not valid for large volumes such as barns or warehouses: a warehouse of 1,000 m^2 (1,200 square yards) and 10 m high (33 ft) represents 10,000 m^3. In practice, such large volumes are unlikely to be airtight anyway.

Volume computation

Fire needs air; if water vapour pushes all the air away, the fuel can no longer burn. But the replacement of **all** the air by water vapour is harmful for firefighters and other people still in the building: the water vapour can carry much more heat than air at the same temperature (one can be burnt by water vapour at 100 °C (212 °F) above a boiling saucepan, whereas it is possible to put an arm in an oven—without touching the metal!—at 270 °C (520 °F) without damage). This amount of water is thus an *upper limit* which should not actually be reached.

The *optimal*, and minimum, amount of water to use is the amount required to dilute the air to 15% oxygen: below this concentration, the fire cannot burn.

The amount used should be between the optimal value and the upper limit. Any additional water would just run on the floor and cause water damage without contributing to fire suppression.

Let us call:

- V_r the volume of the room,
- V_v the volume of vapour required,
- V_w the volume of liquid water to create the V_v volume of vapour,

then for an air at 500 °C (773 K, 932 °F, best case concerning the volume, probable case at the beginning of the operation), we have[1]

$$V_v = 3571 \cdot V_w$$

and for a temperature of 100 °C (373 K, 212 °F, worst cas concerning the volume, probable case when the fire is suppressed and the temperature is lowered):[2]

$$V_v = 1723 \cdot V_w$$

For the maximum volume, we have:

$$V_v = V_r$$

considering a temperature of 100 °C. To compute the optimal volume (dilution of oxygen from 21 to 15%), we have[3]

$$V_v = 0.286 \cdot V_r$$

for a temperature of 500 °C. The table below show some results, for rooms with a height of 2.70 m (8 ft 10 in).

Amount of water required to suppress the fire volume computation

Area of the room	Volume of the room V_r	Amount of liquid water V_w	
		maximum	**optimal**
25 m² (30 yd²)	67.5 m³	39 L (9.4 gal)	5.4 L (1.3 gal)
50 m² (60 yd²)	135 m³	78 L (19 gal)	11 L (2.7 gal)
70 m² (84 yd²)	189 m³	110 L (26 gal)	15 L (3.6 gal)

Note that the formulas give the results in cubic meters; which are are multiplied by 1,000 to convert to liters.

Of course, a room is never really closed, gases can go in (fresh air) and out (hot gases and water vapour) so the computations will not be exact.

Notes

> *Note 1*: indeed, the mass of one mole of water is 18 g, a liter (0.001 m³) represents one kilogram i.e. 55.6 moles, and at 500 °C (773 K), 55.6 moles of an ideal gas at atmospheric pressure represents a volume of 3.57 m³.
>
> *Note 2*: same as above with a temperature of 100 °C (373 K), one liter of liquid water produces 1.723 m³ of vapour
>
> *Note 3*: we consider that only V_r - V_v of the original room atmosphere remains (V_v has been replaced by water vapour). This atmosphere contains less than 21% of oxygen (some was used by the fire), so the remaining amount of oxygen represents less than $0.21 \cdot (V_r - V_v)$. The concentration of oxygen is thus less than $0.21 \cdot (V_r - V_v)/V_r$; we need it to be 0.15 (15%)

Thermal computation

In the case of a fire in a closed volume, the first concern is to lower the temperature. In the worst case, we can consider that it is necessary to absorb all the heat produced by the fire (in practice, only a part of the heat must be absorbed to extinguish the fire). The heat is transferred to the smoke, walls, ceiling, floor; part of it is carried away with the smoke by ventilation, or through poorly insulated walls. The most critical point is to absorb the heat of the smoke inside the room, and to lower the temperature, although not down to the normal ambient temperature of 20°C (68°F). The computation made with this hypothesis is thus the calculation of a maximum, the amount that is really required is smaller.

If the room is totally airtight, the fire will stop spontaneously when the concentration of oxygen drops below 15%. The volume of oxygen used for this is $0.06 \cdot V_l$.[4]

A cubic meter of oxygen combined with a fuel typically produces 4,800 kcal, i.e. 20 MJ.[5] The rise in temperature from 20 to 100 °C (68 to 212 °F) and the vaporization of one liter of water absorbs 539,000 kcal (2,260 MJ).

The volume of water V_w' that is required to absorb the heat is thus:[6]

$$V_e' = 0.00053 \cdot V_l$$

Amount of water required to suppress the fire
thermal computation

Area of the room	Volume of the room V_l	Amount of liquid water V_w'
25 m² (30 yd²)	67.5 m^3	36 L (8.6 gal)
50 m² (60 yd²)	135 m^3	72 L (17 gal)
70 m² (84 yd²)	189 m^3	100 L (24 gal)

Note that the formula gives the result in cubic meters; it is multiplied by 1,000 to convert to liters.

Notes

Note 4: the concentration of oxygen dropped from 21% to 15%, the volume of oxygen involved represents 21-15 = 6% of the volume of the room

Note 5: for example, the combustion of 1 m^3 of methane requires 2 m^3 of pure O_2 and generates 35.6 MJ ; 1 m^3 of O_2 thus contributes to the creation of 17.8 MJ (4,250 kcal);

Note 6: $V_w' \cdot 2260 = 0.06 \cdot V_r \cdot 20$ in megajoules, thus $V_w' = 5.31 \cdot 10^{-4} \cdot V_r$;
$V_w' \cdot 539000 = 0.06 \cdot V_r \cdot 4800$ in kilocalories, thus $V_w' = 5.34 \cdot 10^{-4} \cdot V_r$;
the difference of 0.6% between the values is due to the approximations, and is negligible

Conclusion

Let us compare the calculated values:

Amount of water required to suppress the fire comparison of computations

Area of the room	Height of the room	Amount of water		
		Volume computation		Thermal computation
		Maximum	Optimal	
25 m^2 (30 yd^2)	2.7 m (8 ft 10 in)	39 L (9.4 gal)	5.4 L (1.3 gal)	36 L (8.6 gal)
50 m^2 (60 yd^2)	2.7 m (8 ft 10 in)	78 L (19 gal)	11 L (2.7 gal)	72 L (17 gal)
70 m^2 (84 yd^2)	2.7 m (8 ft 10 in)	110 L (26 gal)	15 L (3.6 gal)	100 L (24 gal)

We can see that both computations give closely similar values. This means that the amount of water required to cool the smoke is sufficient to make the atmosphere inert, and thus to suppress the fire.

Taken from http://en.wikipedia.org/wiki/Fire_fighting#Closed_volume_fire

3. Direct Firefighting - A recent survey[5] undertaken, by Grimwood, 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! It is disconcerting that the UK firefighting flow-rate has actually halved since 1990 without any directive to do so. This reduction in flow-rate has evolved through a mis-match in equipment between pumps, hoses and nozzles currently in use and the recent BDAG research[6] was clear to point this out. It has also been somewhat encouraged where total reliance in the Swedish method of pulsing water-fog has become our primary focus for fire attack, despite its obvious limitations. The 40lpm flow-rate 'pulsed' so effectively at a 1.5MW *container* training fire is impractical in a 75m3 bedroom (for example) that presents a potential for sudden development to heat release rates of 7-10MW (up to seven training fires in one)! So if 40lpm is inadequate for anything but the very smallest of room & contents fires, what is the *minimum safe flow* that firefighters should be equipped with?

- 25% of fires were suppressed @ 1.25lpm/m2 flow-rate
- 21% of fires were suppressed @ 1.87lpm/m2 flow-rate
- 21% of fires were suppressed @ 2.75lpm/m2 flow-rate
- 17% of fires were suppressed @ 3.75lpm/m2 flow-rate
- 16% of fires were suppressed between 0.62-1.25lpm/m2 flow-rate

Table 1 – The author's 120-fire study[7] recorded flow-rates that clearly correlated with the extent of fire damage. Where the fire-ground flow-rate dropped below 2.0lpm/m2 (50% of occasions) the structure fires were only suppressed during the decay phase on the fire development curve. Decay-phase fires are more likely to subject buildings or compartments to structural collapse and should be avoided. These fires were all serious working fires that occurred within an inner city environment and involved a wide range of occupancies.

Tactical Flow-Rate

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.*

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.

There have been several attempts to estimate reliable *efficiency factors*[8] 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 0.33. Thus it was proposed by some researchers 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[9] based on extensive real fire data[10] 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 'jet' 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 is seen to be closer to 1 MW and at 600deg.C it is close to 1.2 MW.

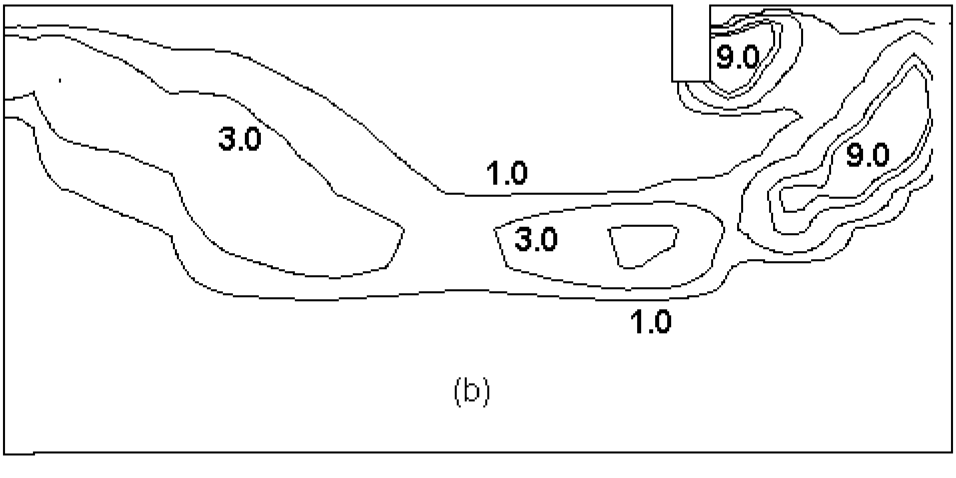

Fig.1 – This side view model of a room & contents fire demonstrates that heat release is dynamic and shows how fire gases will burn hotter at ventilation points (ie; the entry doorway) creating more severe conditions for advancing firefighters. In these situations, an effective flow-rate to overcome gaseous-phase combustion is essential. What is presented as a 5MW room fire overall may actually display twice the amount of heat release at entry points to the room.

Cliff Barnett (New Zealand) has possibly contributed more to the engineering concepts associated with firefighting flow-rate than any other. His computer modelling of design fire flow-rate requirements is well established on a global platform and his most recent research for the SFPE NZ is based upon efficiency factors[9] that offer far greater accuracy when applied to 'real-world' empirical research.

In combining Cliff Barnett's SFPE NZ engineering research[9] with my original fire-flow calculations based on real fire data[7], the updated *efficiency factors* are inserted by Barnett into his flow-rate calculations as follows -

Example 1
Find the total heat energy absorbed (Qs) 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

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

Example 2
If the efficiency of a fog nozzle delivery at 7 kg/s is only 75%, find the total heat energy absorbed.

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

Example 3
If the efficiency of a jet nozzle delivery at 7 kg/s is only 50%, find the total heat energy absorbed.

Qs = 7 kg/s x 2.6 MJ/kg x 0.50 = 9.1 MW

Example 4
An office 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 m x 6 m x 0.25 MW/m² = 9.0 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 2 and 3 above).

Example 5
Combining efficiencies associated with compartment burning rates restricted due to ventilation factors and water efficiency factors might see the formula develop as follows (where F = Needed Flow-rate) –

F = (0.50 x 10.0 MW) / (0.50 x 2.6 MJ/kg) = 3.84 kg/s

This use of the Barnett formula suggests a 10MW compartment fire burning at 50% efficiency due to restrictions on available ventilation openings, presenting an efficiency factor of 50% for a direct 'jet' stream would require 3.84 kg/s (230lpm) to effectively control this fire during the growth or steady-state stages of development.

For further information visit www.fire-flows.com

4. Compressed Air Foam Systems – Coming soon!