Training with intent – effective hose stream techniques

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Effectiveness

How do we know our training is effective? Most people would say that we should ultimately judge the effectiveness of our training by how well we perform on the fire ground. So that begs the question, how do we measure our performance on the fire ground? How do we know whether our training is actually increasing our capabilities (or inhibiting)? In particular how do we know our hose stream training is effective and that those techniques are as effective as they can be when they are used to control the interior environment and ultimately extinguish the fire?

Image 1. Australian firefighters practice 'gas cooling'.

Similarly how do we judge if a crew has been as effective as they could be at a real incident given the circumstances and equipment at their disposal? If a crew appears to perform poorly at an incident is it fair to say they were poorly trained or did they do the best given the circumstances confronting them?

Or conversely was the firefighter well trained but for whatever reason is always a poor performer (lacking motivation, less capable physically or maybe incapable of understanding the theory)? Or would another crew with better skills have had better outcomes? What gauge do we use to measure whether our firefighters were 20% effective, 50% or higher? Or is there a convenient assumption that we are always as effective as we can possibly be?

The key question remains. If we hope to have high performing firefighters we must be able to measure their effectiveness and measure their improvement during training and on the fire ground.

Does science have the answer?

Scientifically we seek to provide objective answers to some of the questions above. This is done by attempting to measure and then record an event that is quantifiable. These events can be careful laboratory experiments or even larger acquired structure burns. By doing so we hope to establish a 'benchmark' from which we can judge whether we are meeting our objectives and if not, why.

Without this 'scientific method' and the controls and discipline that it brings, our ability to assess firefighter effectiveness will always be tainted by personal bias and anecdotal evidence which makes up what most of us call 'experience'. Unfortunately experiences can vary greatly from firefighter to firefighter and even firefighters attending the same fire can come away with very different experiences, all 'valid' from their personal point of view. Therefore it should come as no surprise that firefighters from different countries can differ greatly on what are the most effective tactics and techniques.

Variables, variables and more variables!

The problem when applying the scientific method to firefighting is that there are so many variables on the fireground. Accurate and repeatable scientific experiments rely on identifying and controlling variables. But this presents a problem because the more variables that you remove from experiment the less 'realistic' it may be. In effect, we are trying to introduce control and order to a situation that can be the exact opposite. No wonder for the average firefighter there can be more than a little mistrust (for some outright disbelief) in the findings from the 'lab' when this is not what they believe they are witnessing first hand at the fires they are attending. It also leads to the inevitable comments like, 'That's fine for your experiments, BUT WHAT IF…?' (add here any number of variables, both real and imagined).
Now this doesn't mean that science don't have a place on the fireground, of course it does. In fact it is the best way in which we can further our knowledge and better understand the challenging environment that we work in. In the past experience was our substitute for knowledge in the sense that more experience assumedly led to greater knowledge. In fact culturally, many firefighters were indoctrinated to believe that experience was equal to knowledge. One came to accept that if a firefighter had been to many fires then by definition, they would be more knowledgeable. If only it was that easy! And while I can rationalise this as I sit here and type, I know myself that I often fall into the trap of believing that my own experiences and time as a firefighter credits me with more knowledge than I truly have.

On the fireground

If we look at the fireground in general we can see a number of variables that play a part in how effective we will perform during an incident. There are a number of important factors where our actions (and decisions) based on the prevailing variables can affect performance. How advanced was the fire? Did we choose the correct strategies? Were we slow or fast in implementation of that strategy? We can have crews that arrived late but employed the correct strategy or crews that arrived early but employed the wrong strategy. Crews that used the right techniques with the wrong equipment or the right equipment with the wrong techniques. Or crews trying to implement the right tactics without enough firefighters or the wrong tactics with sufficient firefighters.

If life wasn't hard enough, there are variables within variables! If we look at hose stream techniques for instance. The technique that the firefighters are using may or may not be the most appropriate technique for the situation. Furthermore, assuming it is the right technique, it could be then be performed well or badly. And drilling down even further, whether a technique is performed well or badly is determined by its own subset of variables. The chart below (*Figure 1.)* looks at the variables or actions involved when firefighters use an 'indirect attack' during extinguishment. The differing possibilities for the variables on this chart alone can lead to nearly one thousand possible outcomes.

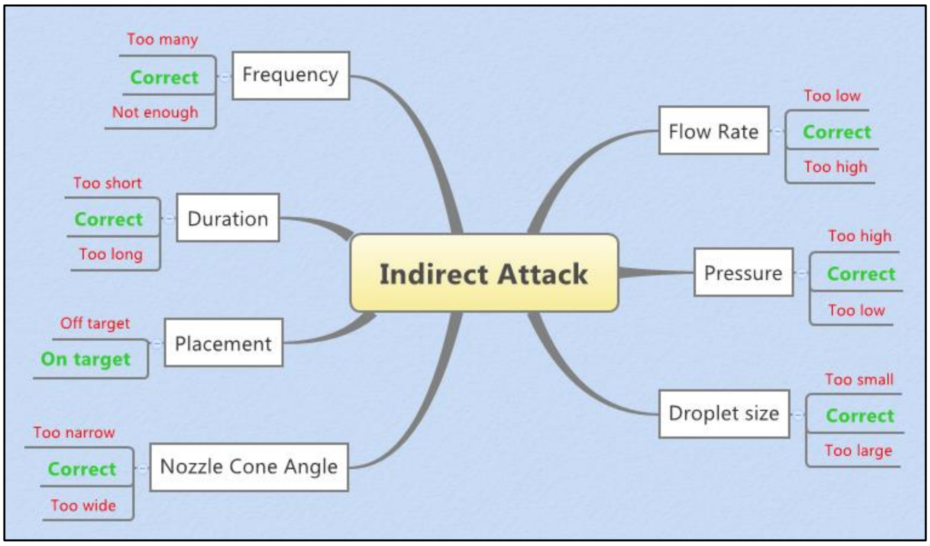

Figure 1. Indirect Attack extinguishment variables.

This type of extinguishment can be very effective when used appropriately and in particular when extinguishing fully involved compartments. It does this in a number of ways:

1. absorbs heat - water drops increase in heat and turn to steam
2. 'inert' the fuel mixture and displace air (oxygen)

For maximum efficiency these two phenomena rely on a number of actions being done correctly. Some of the actions could be considered more important than others while other actions are closely linked. For example, to achieve the correct 'droplet size' we must combine the correct *'flow rate'*, *'pressure'* and *'cone angle'* (this is assuming that we have a nozzle that is capable of producing the correct droplet size). Likewise the *'duration'* and *'frequency'* of the water application is of little effect if the *'placement'* is not accurate. To perform the very best, most effective indirect attack, all seven factors must be performed correctly.

Extinguishing with Water

Before we go too much further, perhaps it's time to look closer at how water is used to control and extinguish fire. Water is applied in a liquid form to the fire and is transformed into steam. The absorbed heat consists of several components.

Specific heat of water

A certain amount of energy is needed to heat a quantity of water. This value is known as the specific heat of water. It is indicated with the letter c. Its unit is J/kg K. This value is 4,186 J/kg K for water.

When water is used to cool gases, a short pulse is given in the smoke layer. Energy will be transferred from the smoke to the cold water droplets until the water reaches a temperature of 100° C (373 K). The amount of energy is calculated by multiplying the mass (m) by the specific heat (c) and the raise in temperature (ΔT). This leads to the following formula:

$$Q = m \times c \times \Delta T \qquad [\,J\,]$$

Latent heat of vaporization of water

Water will absorb even more energy to vaporize. This value is known as the latent heat of vaporization of water. It is indicated with the letter L. Its unit is kJ/kg. This value is 2,260 kJ/kg for water. Energy will be transferred from the smoke to the hot water droplets until the water is completely vaporized. The amount of energy is calculated by multiplying the mass (m) by the latent heat (L). This leads to the following formula:

$$Q = m \times L \qquad [J]$$

When both values (c and L) are compared, it is clear that the transition from 100° C water into 100° C steam absorbs more energy than the heating of the water until it reaches 100° C. Six times more energy is needed to transform the water into steam than is needed to heat the water.

Specific heat of steam

When the steam is dispersed into the smoke layer, more energy will be transferred from the smoke layer to the water vapour. The result will be a rise in steam temperature. This process will continue until a thermal equilibrium exists between the steam and the smoke.

Steam has a different value for the ‘specific heat’ than water. This value is dependent on the temperature of the steam. For this calculation an average value is used. This value is 2,080 J/kg K. The formula used is the same as the one used for water.

The temperature difference (ΔT) is the difference between the end temperature of the steam and 373 K. In order to do a calculation an assumption must be made for the end temperature of the steam. In this document, the value of 300° C (573 K) will be used.

Total absorbed heat

Ideally, when water is used to cool the smoke layer, all the water that is used is being transformed into steam. To estimate the amount of energy that is absorbed, the three ‘heat’ components need to be added. When adding the influence of temperature (of water from a hydrant), the following result is obtained:

T (°C)	Q (MJ/kg)
10	3.05
15	3.03
20	3.01
25	2.99
30	2.97

Table 1 Total absorbed heat per kg of water in function of the hydrant water temperature

It can be observed that the influence of the starting temperature is limited. In order to simplify our calculations, we shall use 3MJ/kg as default value for the amount of energy that one litre of water can absorb. When the fire service uses water, it will rarely lead to such a high value and we will never be 100% effective.

Figure 2. Belgian firefighter practices hose stream techniques.

Vapour formation

When water is turned into steam it expands. One litre of water will generate a large quantity of steam. This can be calculated with the universal gas law.

$$p \times V = n \times R \times T$$

With p being the pressure in Pascals (Pa), V being the volume in m³, n being the number of moles of molecules of the gas at hand, R being the universal gas constant (8.314 J/kg K) and T being the temperature in Kelvin (K). When the equation is solved for V, the following solution is found:

$$V = \frac{n \times R \times T}{p} \qquad [m^3]$$

The molecular weight of water is 18 g/mole. Therefore, 55.55 moles of water are present in one kilogram (litre) of water.

The end temperature of the steam will determine the quantity of steam that is produced by one litre of water. In the table below a series of values is given.

T (°C)	V (m³)
100	1.70
200	2.16
300	2.61
400	3.07
500	3.52
600	3.98

Table 2 Steam volume of 1 litre of water as function of final steam temperature

Steam is an inert gas. This is an important factor in firefighting. When steam is added to a gas mixture, its flammability range shrinks. At a certain point, the mixture will no longer be flammable and therefore rendered inert.

Influence of droplet size

The size of the droplet is an important parameter. If the droplets are very small, they will evaporate too soon after leaving the nozzle and only the smoke layer closest to the firefighter will be cooled. If the droplets are too large, they will pass through the smoke layer without evaporating completely. Some may hit the ceiling and will evaporate there absorbing heat from the ceiling. Another possibility is that they drop to the ground. In this case they will travel through the smoke layer a second time. Grimwood suggests that 0.3 mm is the ideal size for a droplet. Droplets this size should be large enough to provide penetration into the hot smoke and yet small enough to vapourize readily.

Now we have an understanding of the basic science behind using water the next step is to integrate that knowledge together with our ongoing assessment of firefighter effectiveness. In doing so, we can provide some measurement to help more accurately assess our level of capability. Ultimately, it can provide a basis to determine minimum flow rates, number of hose lines, crew sizes and tactics and strategies. Let's now look at how we can perhaps present the somewhat '*subjective'* firefighter actions into something we can 'plug' into the science.

Using and Understanding Rubrics

The key to assessing our effectiveness is to recognise that certain variables or criteria exist and to identify them. Once this is done we can assign levels of 'value' to each variable against which performance levels can be compared. One way of assessing our performance is to use assessment 'rubrics'. A rubric matches set criteria against a 'performance' value. This value can be numerical such as a percentage value or a description of the performance such as 'adequate' or 'poor'. It can also be used to define a level of competency i.e., 'competent' or 'not yet competent'. It also includes a description (or example) that illustrates that level of performance. Rubrics are an excellent way for firefighters to understand the elements that comprise a skill or technique and how to achieve high performance. It can also provide a matrix from which trainers can assess that performance.

Table 3. Shows a rubric for assessing the effectiveness of short pulse gas cooling. The matrix is composed of:

1. important *criteria* that are deemed necessary for performing the technique;
2. a *performance* standard and
3. a *description* of the different performance indicators.

The rubric can be used in a number of ways. Firstly we can assess an individual criteria, for example, 'nozzle angle'. This is the angle that the nozzle is held relative to the floor. This is extremely important with regard to the placement of the water droplets. As the small descriptive image shows, if the nozzle is approx. 45° to the horizontal all of the droplets will end up in the fire gases achieving a greater than 75% efficiency. Conversely, if the nozzle angle is only 25° most of the droplets will end up on the floor instead of cooling gases. As a result the angle is assessed as achieving less than 25% efficiency. A similar distinction is also made for the other criteria such as 'droplet size' and 'cone angle'.

As well as looking at each of the criteria separately, the matrix can be interpreted more globally. Simply put, if we have the most effective droplet size, cone and nozzle angle we can expect to be at least 75% effective for that technique overall. But if we have the correct droplet size but the wrong nozzle angle we will be correspondingly less effective. As noted earlier, some of the criteria are closely linked. For example cone angle and droplet size. It is not possible to have the correct droplet size (or even a droplet at all) if the cone angle is too narrow or a straight stream. However droplet size and cone angle are not affected by the nozzle angle.

The linked nature of some of the criteria should be noted when viewing the rubric from a 'whole of technique' basis.

Gas Cooling - Short	**Effective** Greater than 75%	**Adequate** 75% to 50%	**Ineffective** 50% to 25%	**Poor** Less than 25%
Droplet Size (average)	0.3 mm	0.2 mm or 0.4 mm	0.1 mm or 0.5 mm	< 0.1 mm or >0.5 mm
Cone Angle	45°	30°	90°	120°
Nozzle Angle (from the horizontal)	45° plus		25°	0°
	COMPETENT		**NOT YET COMPETENT**	

Table 3. Short Pulse Gas Cooling Rubric.

Image 3. Cone angle vs nozzle angle.

Making Sense of the Science

There is another important use for the rubric. The advantage of developing a rubric for each of our hose stream techniques means that we now have some level of quantative measurement for how effective our firefighters are with their water usage. Is it perfect? No, but it can help us make sense of the science of extinguishing with water. As the science is explained below, an important variable in the equations is the efficiency %. This percentage can be taken from the rubrics. Let's have another look at the extinguishing technique of 'indirect attack'.

Indirect attack works in two ways:

- Heat is extracted from the enclosure.
- Water vapour is rendering the environment inert since it expels the oxygen from the environment.

Heat absorption

The fire produces a heat. The heat release rate determines how intense the fire is. The HRR is expressed in kW (or MW). It indicates the quantity of energy that is produced per unit of time.

Example:

A 3 MW fire releases 3 MJ per second. When such a fire burns for ten minutes, a total quantity of 1800 MJ (or 1.8 GJ) have been produced.

$$Q = HRR \times \Delta T$$
$$= 3\, MJ/s \times 600\, s = 1800\, MJ$$

In order to calculate the cooling capacity of a fire flow, the flow rate (q in kg/s) has to be multiplied by the total absorbed heat for 1 kg of water.

$$\dot{Q} = Q \times q \quad [MW]$$

As mentioned before, this value will only be realized if the efficiency is 100%. In reality, firefighter efficiency will rarely be 100%. Values as low as 50% or 25% are more likely (see the rubric). Lower efficiencies are caused by water that flows away before being transformed into steam and the steam that flows out of the enclosure before being heated to 300 °C. The effect of the efficiency can be seen in the table below. Less efficient firefighters can lack serious capability!

Efficiency (%)	$\dot{Q}$(MW)
100	11.49
75	8.62
50	5.75
25	2.87

Table 4 Cooling capacity of a 230 lpm flow rate as function of firefighter efficiency

When the heat absorption capacity of the flow exceeds the heat production of the fire, the fire will be extinguished. When the heat of the fire is absorbed by the water, it can't be used anymore to cause pyrolysis and feed the fire. In the table it can be seen that it is possible to extinguish the fire with a 50% efficient firefighter. If the efficiency drops to 25%, the firefighter will have difficulty in extinguishing the fire. Typically it will take more time and more water to do so.

Of course, it is important to consider that there is a geometric limit to this. In an apartment, there may be a fire in multiple rooms. It will not be possible to apply water in multiple rooms simultaneously using only one nozzle. Another example is a fire in a hall. Physically, it is not possible to disperse water droplets in the complete volume in only one second of time. In such cases, multiple lines can provide a solution.

Inerting effect

The total quantity of steam can be calculated by multiplying the generated volume per litre by the flow rate.

$$\dot{V} = V \times q \qquad [m^3/s]$$

With V being the volume of steam generated by one litre of water (m³/kg) and q being the flow rate (kg/s).

Once again, the flow will never be 100% efficient. A portion of the steam will flow out of the enclosure through windows and doors. On the other hand, the volume doesn't need to be filled completely with steam to extinguish the fire.

It is very important to realize that the water vapour contributes greatly to the extinguishment effect. Indirect attack is capable of extinguishing fires with a HRR that is higher than the amount of heat that can be absorbed by the heat absorption capacity of the flow. During indirect attack, the two effects (cooling and inerting/diluting) are both playing an important role. (Note: the reader should realize that this combination of the two effects is more complex than what is explained in this paper).

An example of the science in action:

The water coming from the hydrant is 10° C. This corresponds to 283 K. The water droplets will be heated to 100° C (373 K). The difference in temperature is 90 K. One litre of water is used. This corresponds to 1 kg.

$$\begin{aligned} Q &= m \times c \times \Delta T \\ &= 1 \times 4{,}186 \times (373 - 283) \\ &= 376{,}740\, J = 376.74\, kJ \end{aligned}$$

The amount of energy needed to turn the water into steam is:

$$\begin{aligned} Q &= m \times L \\ &= 1 \times 2{,}260{,}000 \\ &= 2{,}260{,}000\, J = 2{,}260\, kJ = 2.26\, MJ \end{aligned}$$

In the example above, 376 kJ is used to heat the water and 2,260 kJ is used to transform the water into steam. This means that 6 times more energy is needed to transform into steam than is needed to heat the water. The steam will be heated to 300 °C (573 K). The difference in temperature is 200 K.

$$\begin{aligned} Q &= m \times c \times \Delta T \\ &= 1 \times 2{,}080 \times (573 - 373) \\ &= 416{,}000\, J = 416\, kJ \end{aligned}$$

The water coming from the hydrant has been heated to a temperature of 100° C and has been transformed into steam of 300° C.

$$\begin{aligned} Q &= Q_1 + Q_2 + Q_3 \\ &= 376.74 + 2{,}260 + 416\, kJ \end{aligned}$$

$$= 3{,}052.74\ kJ = 3.05\ M$$

In the calculations above, the resulting steam temperature was 300° C (573 K). This leads to the following quantity of vapour.

$$V = \frac{55.55 \times 8.314 \times 573}{101{,}325} = 2.612\ m^3 = 2612\ l$$

When a similar calculation is performed to estimate the effect of indirect attack, the following result is found:

A firefighter uses a low pressure nozzle with a flow rate of 230 litres per minute. The flow rate in kg/s is calculated as follows:

230 lpm = 3.83 lps = 3.83 kg/s

$$\begin{aligned} \dot{Q} &= Q \times q \\ &= 3MJ/kg \times 3.83\ kg/s \\ &= 11.49\ MJ/s\ = 11.49\ MW \end{aligned}$$

A cooling capacity of 11.49 MW means that every second, a quantity of heat of 11.49 MJ can be absorbed. When working at a 100% efficiency, the following amount of steam is produced.

$$\dot{V} = 2.61 \times 3.83 = 10\ m^3/s$$

A fire in a room is attacked by the fire service with a flow rate of 230 lpm. The dimensions of the room are 4 m by 5 m by 2.5 m. The volume of the room is 50 m³. When the flow is 100% efficient, a steam volume of 50 m³ will be generated after 5 seconds of applying water. This will cause the extinguishment of the fire because the generated steam will have displaced all the oxygen.

Doing the simple things well

The science shows us that there is a significant difference between firefighters who can place their water in the right format, in the right place and at the right time and those that can't. A firefighter who is 75% efficient with their water has nearly three times the extinguishing power of a firefighter who is only 25% effective. The difference to the untrained eye may only be a slight variance in cone angle, nozzle angle or droplet size but the end result is that the water is not getting where it needs to go. With three time less extinguishing power, low performing crews will place themselves in more danger and take longer to impact.

By utilising such methodologies as assessments rubrics, we can provide firefighters with an easily understood matrix from which to critique their skill level and identify where they can improve. By understanding the science, firefighters can see the effects of correct technique and realise the benefits of developing and maintaining their skills. By training hard and learning to perform the basic hose stream techniques well, firefighters will not only be safer but provide a better service to the community.

Sources

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