Rate of Flow Formulas for the Fire Service
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One of the most important questions relating to fighting fires is the following.

How much water is needed to fight a given fire?

Immediately it should be recognized that the answer to this question varies as the size of the fire. The bigger the fire, more water is needed to control or extinguish that fire. Also the answer varies as the type of fire (Class A, B, or C), as well as the type of structure involved (ordinary or noncombustible) Thus we are dealing with complex answers to a simple question..

It is necessary, therefore, to narrow the question be able to get an answer. Let's narrow the question to ordinary Class A fires that are confined in a structure. Thus our question becomes,

How much water is needed to fight ordinary confined structure fires?

Confined structure fires are the type most frequently encountered by all fire departments (brigades), and are of greatest concern for life safety and property conservation. The definition of a confined structure fire is one in which the ceiling or roof is intact. This definition means that a fire can be burning out a window(s) or a door(s) and still be a confined fire.

There is an answer to the previous question. Before considering this answer, however, we must introduce some elementary mathematics. Elementary mathematics does not mean the math that is taught in elementary schools, but the algebra that is taught in high schools throughout the United States and in other countries at the same level.

Fire departments do not have the means or capability of dumping all the water needed onto a fire all at once. We use nozzles that flow water over a period of time. At the end of that time enough water will be projected into the fire to control it or extinguish it. The time involved may be very short (seconds) for confined fires. For a large structure in which fire has burned through the ceiling and roof (open fire), the time involved may be hours. In either case water is flowing at a certain rate for a certain period of time. Thus we must study the rate-of-flow formula (equation) to answer our question of how much water is needed.

The rate-of-flow formula is an equation that states a relation between three numbers. The first number is a rate-of-flow (r.o.f) expressed in gallons per minute (Gpm) in the English system of measurement, or by Liters per minute (Lpm) in the SI (metric) system. Two examples are:

100 Gpm 378.5 Lpm

Since one gallon equals 3.785 liters, 100 Gpm = 378.5 Lpm, that is, the same r.o.f. Note carefully what this number says. It is a flow of a certain number <u>per minute.</u> The flow is not just for one minute, but for a second minute, and so on. It is true for every minute, or all minutes. Thus this number is a quantified number. It is true for all minutes, hence the name-the universal quantifier.

The second number is time expressed in minutes. Flowing water at a certain rate for a certain time produces a certain amount of water at the end of that time. This means that the third number is the total amount of water applied. The relation between these three numbers is expressed in the following r.o.f. equation.

$$\text{Gpm} \times t = \text{Gal} \qquad\qquad \text{Lpm} \times t = \text{L}$$

These symbols are defined as follows.

Gpm = gallons per minute
Lpm = liters per minute
t = time in minutes or fraction of a minute
Gal =number of gallons
L = number of liters
x = multiplication
= is equals

This basic rate formula is used in all sciences applied to many different things using different symbols. Let's take one example. In physics, there is the distance formula.

r x t = d

With r = miles per hour, t = time in hours, and d = distance in miles. (Metric formula is S x t = km with S = km/hour).

For you to be able to use these formulas, you must understand several things.

- First, you must understand the meaning of the quantified number, the gallons per minute, or the kilometers per hour.
- Second, in order to solve a problem using this formula you must be given values for two of the three variables..
- Third, then you must decide whether to multiply or divide to get the answer to the problem. This is easy to do if you understand the basic rule for manipulating an equation.

Let's proceed to solve several problems involving the r.o.f. formula.

Suppose that Gpm = 100 and that t = 2 (Lpm = 378,5 and t = 2). Substituting into the r.o.f. formula gives

Gpm x t = Gal   Lpm x t = L

100 x 2 = Gal   378,5 x 2 = L

Logically if water is flowing for one minute, then flowing for two minutes gives you twice as much. Thus multiplying the two numbers makes sense. This is how the equation is solved to get the answer.

200 = Gal   757 = L

Let's take another example with t = 30 seconds. Since r.o.f. time is "per minute" the r.o.f. time must be expressed as a fraction of a minute. Instead of 30 seconds, therefore, 0.5 of a minute must be used.

Gpm x t= Gal   Lpm x t = L

100 x 0.5 = Gal   378,5 x 0.5 = L
50 = Gal   189,25 = L

The only time for which the r.o.f equals the total amount of water is when time equals one minute.

100 x 1 = 100   378,5 x 1 = 378,5

The number "1" is called the identity for multiplication since the product of any number times one equals "identically" the same number.

The remaining two problems involve division instead of multiplication. First suppose you are given a r.o.f. of Gpm = 50 and a total amount of water of Gal = 200. You are asked to find out how many minutes it would take to flow this amount of water at that rate.

$$\text{Gpm} \times t = \text{Gal} \qquad \text{Lpm} \times t = \text{L}$$

$$50 \times t = 200 \qquad 189{,}25 \times t = 757$$

Solving this problem requires you to use the fundamental rule for simplifying equations, namely whatever you do to one side of an equation you must do to the other side. Thus we must divide both sides of the equation by 50.

$$\frac{50}{50} \times t = \frac{200}{50} \qquad \frac{189{,}25}{189{,}25} \times t = \frac{757}{189{,}25}$$

Arithmetic is used to simplify the equation. This gives

$$1 \times t = 4 \qquad 1 \times t = 4$$

Since one is the identity for multiplication, this gives us the answer of t = 4 minutes.

The second problem also requires division. You are given a value for t and for Gal (L). You must calculate the r.o.f. The logic is the same as for the preceding problem. Suppose that you are given t = 5 and Gal = 500 (L = 1.982,5)

$$\text{Gpm} \times t = \text{Gal} \qquad \text{Lpm} \times t = \text{L}$$

$$\text{Gpm} \times 5 = 500 \qquad \text{Lpm} \times 5 = 1.982{,}5$$

In one minute you would flow 1/5 of the total amount of water. In 5 minutes you would flow 5 times as much, or 500 gallons (1.982,5 L). So it makes sense to divide the number of gallons (L) by 5. Doing this produces the answer

$$\text{Gpm} = 100 \qquad \text{Lpm} = 378{,}5$$

Thus far, our r.o.f. formula has only limited use. In order to make the r.o.f. formula really useful, the “Gal” (L) must be replaced by a numerical expression that relates the amount of water used to the size of a fire in a structure. What we are after is an expression that relates the volume of a fire to the volume of the part of the structure that is burning.

This change was first made in 1954 at the Fire Service Institute at Iowa State University by Keith Royer and Bill Nelson. These two men created a formula based upon two scientific facts. The first fact is that the expansion ratio of liquid water to steam is 1/1,700 (1/1.700) at 212° F (100° C). At 212° F (100° C) liquid water is transformed into a gas (steam), and one cubic foot (cubic meter) of liquid water expands instantly to 1,700 cubic feet (meters) of steam` This blast of steam smothers the fire if the fire is confined by a ceiling or roof. Depriving the fire of oxygen immediately stops combustion, hence it controls or extinguishes the fire.

How does this process work to cool a fire? This physical process of transforming a liquid to a gas is an endothermic (heat absorbing) process. In fact, for water, steam absorbs a tremendous amount of heat —968 btus per pound of water (2.257 J/g (Jules/gram)). This is far greater than that of any other substance that could be used to fight a fire. This heat must be retained by steam, otherwise it condenses back to liquid water. Also it is important to remember that this process does not raise the temperature of steam above 212° F (100° C). The capacity of water to absorb heat to create steam is called the enthalpy of vaporization of water.

Steam is highly effective in fighting fires because the temperature of 212º F (100º C) is well below the temperatures needed to start a fire. The ignition temperatures of hydrocarbon fuels range from 400º F (204º C) to 500º F (260º C) and upward. After ignition fire temperatures range upward to 1,000º F (537,7º C) at flashover and on upward. When steam is created in a confined fire, the temperature rapidly drops in less than one minute to around 300º F (148,8º C). This temperature is below ignition temperatures but still above 212º F (100º C), the temperature at which steam is created. Firefighters can operate in such a steamy atmosphere fully protected without being harmed.

Royer and Nelson created the confined structure fire formula by starting with the liquid water to steam ratio of 1/1,700 (1/1.700) cubic feet (meters) of steam, that is, one cubic foot (meter) expands to 1,700 cubic feet (meters) of steam. Since one cubic foot contains 7.48 gallons, dividing

$$1{,}700/7.48 = 227$$

This is the number of cubic feet of steam produced by one gallon of water. Royer & Nelson rounded 227 down to 200 to allow for a 90% conversion rate of liquid to steam. Thus the Royer-Nelson r.o.f. formula is:

$$\text{Gpm} \times t = \frac{\text{Vol}}{200}$$

Let's use this formula to find out how much water is needed for a confined structure fire. A small room on the average contains about 1,000 cubic feet (28.300 L or 28,3 cubic meters)

$$\text{Gpm} \times t = \frac{1{,}000}{200}$$

$$\text{Gpm} \times t = 5$$

Just five gallons (18,9 liters) is needed to fill this fully involved 1,000 cubic feet (28.300 L) room full of steam. At a r.o.f. of 30 Gpm (113,5 Lpm), this fire can be controlled in a time of

$$30 \times t = 5 \qquad\qquad 113{,}5 \text{ Lpm} \times t = 18{,}9$$

$$t = 5/30 \qquad\qquad t = 18{,}9/113{,}5$$

$$t = 1/6 = 0.166 \qquad\qquad t = 1/6 = 0.166$$

One sixth of a minute equals 10 seconds (60/6). Thus the information that we have is that a r.o.f. of 30 Gpm (113,5 Lpm) applies 5 gallons (18,9 liters) of water in 10 seconds. This can be done easily using a fog nozzle and the combination method of attack. It is easy enough to use this formula to calculate how much water is needed for a 2,000 cubic foot (28,3 cubic meters) or for any other size fire.

The second scientific fact that is the foundation for the Royer-Nelson Formula is the following information. In 1955 the Factory Mutual Laboratories determined that one cubic foot (28,3 L) of pure oxygen combined with ordinary fuels produced 535 Btus (0,564 mJ (megaJoules)). Air contains 21 percent oxygen, and flame production stops when the oxygen level falls below 15 percent. Therefore

$$21 - 14 = 7$$

Only this amount of oxygen, 7 percent of air, is available for flaming combustion. Multiplying this number by the Btus (mJ) produced by a cubic foot (28.3 L) of pure oxygen gives

$$535 \times .{,}07 = 37 \qquad\qquad 28{,}3 \times {,}07 = 0{,}0039$$

37 Btus (0,0039 mJ) is the amount of Btus (mJ) produced by one cubic foot (28.3 L) of air. Because one gallon (3.785 L) expands to more than 200 cubic feet (5.669 L) of steam,

$$37 \times 200 = 7{,}400 \qquad\qquad 0{,}0039 \times 5.669 = 7{,}8 \text{ (mJ)}$$

Since one pound of water absorbs 1 btu/lb to raise the temperature 1ºF, one gallon (8.34 lb) absorbs 150 btus if the temperature is raised from 62ºF to 212ºF. At 212ºF one pound absorbs 968 btus/lb to steam, and 1 gallon absorbs 968 x 8.34 btus, or 8,072 btus/gallon. Thus one gallon (3,785 L) converted to 200 cubic feet (5.669 L) of steam absorbs 9,330 Btus (9,84 mJ). Since 7,400 < 9,330 Btus (7,8 < 9,8 mJ), the conclusion is that one gallon (3,785 L) is capable of absorbing all the heat produced by 200 cubic feet (5.669 L) of air.

It is truly remarkable that both scientific facts converge on the same number. These two facts provide a solid foundation for the validity of the Royer-Nelson formula.

The creation of the Royer-Nelson Formula is certainly a notable achievement in the history of the fire service. From our point-of-view today, what they did may seem to be quite simple. It is true that the expansion ratio of 1/1,700 was widely known in the 1950s. However, at that time very little was known about fire behavior in structure fires. What was known quantitatively was largely in the area of combustion engineering. So when most of the quantitative and qualitative information needed was unknown, the creation of the Royer-Nelson formula stands out as a significant achievement in answering the question

How much water is needed to control a confined structure fire?

The Iowa Rate of Flow Formula

The formula

$$\text{Gpm} \times t = \frac{\text{Vol}}{200}$$

was named by Royer & Nelson "The Gallonage Formula". We have renamed this formula the "Royer-Nelson Formula". This is not the formula that became widely known as "The Iowa Rate of Flow Formula". The Iowa formula can be derived easily from the Royer-Nelson formula. From the research done by Royer-Nelson, they determined that almost all structure fires could be controlled by using fog nozzles in less than 30 seconds. Keith Royer recommended that this fact be used to determine the capability of a fire department to handle its structure fires. So taking the time of 30 seconds (0.5 minute) and substituting into the Royer-Nelson formula gives

$$\text{Gpm} \times 0.5 = \frac{\text{Vol}}{200}$$

Dividing both sides of the equation by 0.5 gives

$$\text{Gpm} \times \frac{0.5}{0.5} = \frac{\text{Vol}}{200 \times 0.5}$$

Simplify by dividing and multiplying

$$\text{Gpm} \times 1 = \frac{\text{Vol}}{100}$$

$$\text{Gpm} = \frac{\text{Vol}}{100}$$

This is the equation known as The Iowa r.o.f. formula. This equation must be interpreted very carefully. The time factor has disappeared from the left side of the equation, and dividing by time on the right produces a different fraction: Vol/100. What has happened is that time has been eliminated from both sides of the equation. V/200 was the product of Gpm x t. Now Vol/100 is only Gpm. So the Iowa Formula is a simple statement that Gpm = Gpm, that and nothing more. No longer are the expressions a product of Gpm x t.

The key to eliminating the confusion is the realization that the Iowa Formula is valid only for a time of 30 seconds. Mathematics has created a notation that helps solve our problem and makes everything clear The solution is to use subscript notation..

Subscript notation uses smaller numerals or letters written below and to the right of a given numeral or expression. Thus the Iowa r.o.f. written as follows is read as: "Gpm for 30 seconds". This notation serves as a reminder that the Iowa formula is valid only for a time of 30 seconds.

$$Gpm_{30s} = \frac{Vol}{100}$$

This is the way the Iowa Formula should be written The Iowa r.o.f. formula should not be compared with any other r.o.f formula with a different time. This second equation should be called the Royer Nelson 30 second formula.

There is a second error that has been made universally in the use of the Iowa r.o.f. formula. The volume of the entire structure should not be used, only the volume of the largest open area of the structure. Keith Royer believed that it would be a rare occurrence that a large building with many rooms would be fully involved before the arrival of a fire department in less than ten minutes. So the fire department's capability should be measured by the largest open area of that structure. The Iowa r.o.f. formula has universally been misused by ignoring the time of 30 seconds and by using it to apply to the volume of the entire structure. Also Keith Royer strongly recommended that the 30 second formula primarily should be used for pre planning.

Let's return to the Royer Nelson formula to consider one of the most significant findings about how much water is needed to fight confined structure fires. This is the discovery that two different research projects in different countries, 36 years apart, completely independent of each other, have arrived at the same answer to the fundamental question

How much water is needed to control confined structure fires?

One of the formulas is expressed in English units while the other is expressed in metric units. So what we must do is to transform the Royer Nelson formula into metric units so that we can compare it with the second formula in metric units.

The mathematics that follows may be tedious, but it is basically simple manipulation of an equation using one fundamental rule. Whatever you do to one side of an equation you must do to the other side. The same rule applies to fractions. We will use the conversion equations for converting from the English system to the metric system. There are two changes to be made, from gallons to liters and from cubic feet to liters. First let's change from gallons to liters. One gallon equals 3.786 liters.

$$Gpm \times t = \frac{Vol}{200}$$

$$(3.785 \times Gpm) \times t = \frac{3.785 \times Vol}{200}$$

The expression (3,785 x Gpm) changes to Lpm, so we will make that change. Next we will multiply the equation by 28.3 which is the conversion number for cubic feet to liters.

$$28.3 \text{ x Lpm x t} = \frac{3.785}{200} \text{ x (Vol x 28.3)}$$

The expression (Vol x 28.3) changes volume from cubic feet to liters. We will use the symbol "Vol_l" to indicate that volume is now in liters.

$$28.3 \text{ x Lpm x t} = \frac{3.785}{200} \text{ x } Vol_l$$

The next step is to divide both sides of the equation by 28.3

$$\frac{28,3}{28.3} \text{ x Lpm x t} = \frac{3.785 \text{ x } Vol_l}{28.3 \text{ x } 200}$$

Since n/n = 1 and 1 x n = n, this simplifies the left hand side of the equation. The numerical fraction on the right side is 3.785/5,660. What we want is to place the quotient in the denominator so that our equation will look like the original Royer Nelson formula. This is purely arithmetic, the manipulation of fractions which produces the following result.

$$\frac{3.785 \div 3.785}{5,660 \div 3.785}$$

And this produces the denominator that we want.

$$\text{Lpm x t} = \frac{Vol_l}{1,495}$$

The number "1.495" may be rounded to the two places to give better accuracy for these calculations.

$$\text{Lpm x t} = \frac{Vol_l}{1,500}$$

Volume is usually expressed in cubic meters. This final change is easy to make in the metric system. One cubic meter equals 1,000 liters, so dividing the numerator and denominator of the fraction (Vol_l / 1.500) by 1,000 produces the following equation with volume symbolized by Vol_m in cubic meters. Also please note that in the metric system "1.5" is written as "1,5" The commas and decimal points are interchanged between the English and metric systems. Perhaps you may have noticed this already in the metric equations previously written. .

$$\text{Lpm x t} = \frac{Vol_m}{1,5}$$

The second formula was published on the internet at www.firetactics.com in 1999 by Paul Grimwood in an article "Compartment & Structural Firefighting, Water Flow Requirements". The formula is

$$\text{Lpm} = \text{A x 2}$$

The formula is in metric unites with Lpm equal to liters per minute, and "A" equals area of a compartment in square meters. It is easy enough to convert this formula to volume by multiplying by ceiling height In addition time is an essential element of any r.o.f. formula, so "t" must be added as well. Multiplying by 3 m (10 ft) gives the formula

$$\text{Lpm x t} = \underline{(3 \text{ x A}) \text{ x } 2}$$

(3 x A) equals volume in cubic meters symbolized by "Vol_m". Simplify this equation by multiplying the numerator and denominator of the fraction by ½ gives the final form of the r.o.f. formula

$$Lpm \times t = \frac{Vol_m}{1.5}$$

This equation is, of course, identical to the Royer Nelson formula in metric units.

What is the significance of this finding? Both formulas were created independently of each other in different countries 36 years apart. Both formulas were the result of careful research. This convergence adds further proof to the validity of the critical r.o.f. formulas. It is safe to say that this formula is the only valid formula that the fire service will ever have to work with for confined structure fires.

Fire Attack

The Royer Nelson Formula is highly suitable for fire attack since it is not restricted to one time of 30 seconds. There are an infinite number of products of time and r.o.f. that equal the right amount of water to fill a room full of steam. However, because most fire fighting is restricted to room size fires, we are restricted to a narrow range of times and flows. Let's consider time first.

We already know from research by Royer & Nelson at Iowa State University that a maximum of 30 seconds is the time needed to control almost all confined structure fires. What is the minimum? An effective fog attack requires that water be distributed throughout the fire area. The method devised by Royer & Nelson to do this is to insert the nozzle inside the room and rotate the nozzle rapidly clockwise as many times as needed to knock out the flames until condensing steam appears. This will take about 10 seconds. That is the minimum time. Let's take the minimum and maximum times and calculate the corresponding flows for a 2,000 cubic foot (56,6 cubic meters), an average size room.

$Gpm \times t = \frac{Vol}{200}$	$Lpm \times t = \frac{Vol_m}{1,5}$
$Gpm \times 0.5 = \frac{2.000}{200}$	$Lpm \times 0,5 = \frac{56,6}{1,5}$
$Gpm \times \frac{0.5}{0.5} = \frac{10}{0.5}$	$Lpm \times \frac{0,5}{0,5} = \frac{37,7}{0,5}$
$Gpm \times 1 = 20$	$Lpm \times 1 = 75,4$
$Gpm = 20$	$Lpm = 75,4$

Now let/s calculate with t = 10 seconds or 1/6 of a minute (0.166 minute)

$Gpm \times 0.166 = 10$	$Lpm \times 0,166 = 37,7$
$Gpm \times \frac{0,166}{0.166} = \frac{10}{0.166}$	$Lpm \times \frac{0,166}{0,166} = \frac{37,7}{0,166}$
$Gpm \times 1 = 60$	$Lpm \times 1 = 227$
$Gpm = 60$	$Lpm = 227$

Thus we need to consider times between 10 seconds and 30 seconds, and flows between 20 gpm (75,4 Lpm), and 60 Gpm (227 Lpm) for room size fires. The Royer Nelson formula gives you all the information necessary to make a powerful fog attack on confined room sized fires.

For larger fires involving more than one room of a structure there are several ways to make an effective fog attack.

- First, make a progressive attack, that is, attack each room in succession, repeating the attack for each room until the entire fire is brought under control.
- Second, use multiple attack lines so that each room is attacked simultaneously, or almost at the same time. This is nothing more than standard strategy for a structure fire which calls for 4 attack lines covering all 4 sides of a structure.
- Third, a larger r.o.f. may be used provided one line can reach all of the fire perhaps with some movement of the nozzle.

How much water is needed to control a larger fire? Let's take a 2,000 square foot (186 square meters) house with a volume of 20,000 cubic feet (566 cubic meters).

$$\text{Gpm} \times t = \frac{\text{Vol}}{200} \qquad \text{Lpm} \times t = \frac{\text{Vol}_m}{1,5}$$

$$\text{Gpm} \times t = \frac{20,000}{200} \qquad \text{Lpm} \times t = \frac{566}{1,5}$$

$$\text{Gpm} \times t = 100 \qquad \text{Lpm} \times t = 377,3$$

According to Royer & Nelson such a fire can be controlled in less than 30 seconds. Using the Iowa r.o.f. formula

$$\text{Gpm} \times 0.5 = 100 \qquad \text{Lpm} \times 0.5 = 377,3$$

$$\text{Gpm} \times \frac{0.5}{0.5} = \frac{100}{0.5} \qquad \text{Lpm} \times \frac{0,5}{0,5} = \frac{377,3}{0,5}$$

$$\text{Gpm} = 200 \qquad \text{Lpm} = 754,6$$

The flow of 200 Gpm (754,6 Lpm) suggests that 2 attack lines should be used with each line flowing 100 Gpm (377,3 Lpm) for 30 seconds. The total amount of water needed is only 100 gallons (378,5 L). There is one catch--you must convert at least 90% of the water applied to steam.

What these examples show is how much water is needed to make a balanced fire attack. This phrase means that you must balance the heat absorbing power of water (steam) with the heat releasing power of a fire. By doing so, the thermal balance that existed before the attack will be restored quickly after the attack, but at a much lower temperature level. The principle governing a balanced fire attack has been stated by Bill Nelson as follows.

> "In principle fire fighting is very simple. All one needs to do is put the right amount of water in the right place, and the fire is controlled".

Notice that Nelson says that the principle is "very simple". In fact, the tactics needed to put this principle into effect are simple enough as well

What is the right amount of water? The right amount, of course, is determined by the Royer Nelson formula. Where is the right place? It is the center of the fire where at least 90% of the water applied will be transformed to steam.

Perhaps we should add to Nelson's principle the phrase, "in the right way". The right way means that a fog nozzle must be used widening the fog pattern so that the stream just reaches across the room. In addition the ideal flow rate must be selected so that the water is distributed throughout the fire area in a few seconds. Finally, the nozzle must be shut down immediately when the flames are gone. So we may change Nelson's principle by adding the following phrase.

> In principle firefighting is very simple. All one needs to do is put the right amount of water in the right place in the right way with a fog nozzle, and the fire is controlled.

Truly Nelson's principle is the most profound statement that has ever been made about fighting fires. Together with the Royer Nelson formula we can answer the question

> How much water is needed to control a confined structure fire?

The answer is: surprisingly little water for fairly large fires. All one needs to do is transform liquid water to steam, and that is simple enough in principle and in actual practice.

Too Little or Too Much Water

What happens if less than the right amount of water is used on a confined fire, or if more than the right amount of water is used? One answer is just common sense. However, the other answer may surprise you..

First, less than the right amount of water. Research at Iowa State University by Royer & Nelson established that less than the right amount of water has less than the desired effect in the fire room. The temperature is this room levels off for a number of minutes but continues to burn at this level. In adjacent areas (hallway, attic, or room) are not affected and the temperature remains at the same level as before the attack and then continues to increase. This is just common sense. Too little water has little effect upon a confined fire Those of us who have attempted to fight a room size fire with a garden hose know exactly how frustrating it is to use too little water on a fire.

Second, what about applying greater than the right amount of water to a confined fire? Common sense tells you that the more water applied to a confined fire, the quicker the fire is brought under control. Not so, for confined fires. Too much water creates thermal imbalance which will disrupt an effective attack and delay bringing the fire under control. The research done by Royer & Nelson at Iowa State University and the research done at the U.S. Naval Research Laboratory both confirm the validity of this statement. What happens is that thermal imbalance, or turbulence, causes temperature spikes both at the lower and at higher levels in the room. This can continue for ten minutes or more. All this blocks visibility, delays entrance in the fire area, because part of the area is too hot and other parts are too cool. Thermal imbalance can be avoided easily by using the right amount of water to control the fire. In other words, there is more to fighting a fire than just opening a nozzle to maximum flow each time you fight a fire. That is robotic fire fighting. A robot acts without thinking.

Now let's shift to another method of attack, the 3D pulse fog attack. For this attack it is critical that the right amount of water be used. The purpose of this attack is to make it safe for an interior crew to approach a fire so as to be able to make direct attack on the fire. If, for example, a crew is proceeding in a hallway toward a fire room, and a rollover threatens their safety, then the 3 D pulse fog attack can remove this threat. However, the right amount of water must be used. Using too much water would fill the hallway full of steam that could scald the firefighters .If the hallway is 25 feet by 4 feet by 8 feet high (7,6 meters by 1,2 meters, by 2,4 meters high) with a volume of 800 cubic feet (22,6 cubic meters), only 4 gallons (15 liters) of water is needed to fill the hallway full of steam. So the 3 D attack must apply a very small amount of water to protect the firefighters in the hallway and at the same time prevent a flashover of backdraft from happening Thus we are back to the fundamental question

> How much water is needed to eliminate the threat of flashover or backdraft?

The answer is certainly less than 4 gallons (15 liters) and no more than one or two gallons (3,78 or 7,56 liters). One gallon (3,785 liters) expands to 227 cubic feet (6,3 cubic meters) of steam. At the same time the fire gases are being cooled by the fog attack which results in a contraction of these gases as the temperature falls from around 1,000º F (537º C) to 300º F (149º C). This contraction must be greater than the steam expansion in order to produce a net contraction in the overhead. Calculations have been made to show that this is actually what happens The 3D pulse attack does work if the nozzle is opened for no more than 2 seconds
For example, if the r.o.f. is Gpm = 30 (113,5 Lpm) and t = 1/30 minute or 2 seconds, then

Gpm x t = Gal	Lpm x t = L
30 x 1/30 = Gal	113,5 x 1/30 = L
1 = Gal	3,8 = L

This amount of water will accomplish the purpose of the 3D pulse attack, prevent flashover or backdraft, and protect the firefighters as they get in position to make a direct attack.

So how much water is needed to make a 3 D pulse fog attack? Very little indeed! One of two gallons (3,78 or 7,57 liters) is surely sufficient to accomplish the purpose of the 3 D attack.

Thornton's Rule

Fire is usually defined as a hydrocarbon air diffusion flame process, that is, a chemical reaction in which hydrocarbon fuels unites with the oxygen in air in diffusion flames which produce heat and light. The fire triangle states that there are three elements needed to ignite or start a fire—oxygen, fuel, and heat. All three elements are needed for ignition to occur. There is a relevant question to ask about this fire behavior.

> Could the amount of fuels or oxygen present affect the rate of heat release in a confined structure fire and nullify the Royer Nelson formula?

First of all, fire engineers are unanimous in agreement that the heat content of fuels has no relation to the rate of heat release in a given fire. What does determine the rate of heat release is the surface area of the fuels involved. It is well known that within the past 50 years plastics have come into widespread use. It is also well known that the heat content of plastics is on the average twice that of ordinary cellulosic (wood based) fuels. Does this mean that fires are hotter today than fires that do not involve plastics? The answer is "no". One expert has said that "If fires are hotter today, plastics have nothing to do with it." Fires may be different today because of better insulation, but it is not necessarily true that all fires are hotter today.

One thing that has not changed is the behavior of plate glass windows in a fire. Plate glass windows break from thermal stress early in the development of a structure fire. This begins at temperatures from 550º F (288º C) to 600º F (316º C). It is a common occurrence for fire to break out a window before flashover occurs. What about double pane windows? In one published test of side-by-side single pane and double pane windows, the double pane window broke out first because the vinyl frame melted. An expert writing in the NFPA Handbook has said, that "Window glazing quickly cracks because of the temperature difference between the surfaces. Double-glazing does not provide much improvement. No glazing should be relied upon to remain intact in a fire." However, there is one type of glazing that behaves differently in a fire. Wired glass contains a net of steel that distributes heat and lowers stress. Wired glass remains intact until 1,470º F (799º C) when it begins to weaken. It will drop out at about 1,600º F (871º C).

Fuels come in a wide variety of compounds with many different properties. However, the second element of the fire triangle involves only one element—the molecular oxygen in air. One of the most important facts about fire behavior of confined fires is that the rate of heat release is limited by the amount of oxygen in the fire area. There is one exception to this at the very beginning of a fire immediately after ignition, in the early flame spread stage. Only a small part of the surface area is involved in fire and the rate of heat release is limited by the fuel surface area available to the fire. Of course, once a structure fire breaks out into the open through the ceiling and roof the fire becomes an open fire with a practically unlimited supply of oxygen

.An important feature of confined fires is that the rate of heat release is limited by the amount of oxygen available. Remember that a fire can be burning out one or two windows, or a door, and it is still a confined fire. More than ¼ the wall area would have to be gone before a confined fire is not longer confined. Thornton's Rule is the key to fire behavior of confined structure fires.. W. H. Thornton discovered his rule in 1917 but it was not used in fire engineering research until fairly recently. Thornton's Rule was published in the 17^{th} Edition of the NFPA handbook in 1991 in Appendix A. Thornton's Rule is stated as follows.

> The heat of combustion per kilogram of oxygen consumed is nearly constant for most organic fuels. It can be shown that the value of
>
> $$\Delta h^1 / r_o = 13.1 \text{ MJ/ kg of } O_2$$
>
> is a near constant. (5622 btus/lb of oxygen)

What this rule means for fire behavior is that while the heat of combustion is quite different for different hydrocarbon fuels, the heat produced per unit of oxygen consumed is the same within about 10% Let's illustrate Thornton's Rule by using cellulose, the common substance of all wood based products, and ethylene a common plastic.

Cellulose $C_6 H_{10} O_5$

Heat of Combustion	16.12 mJ/kg
Ratio O_2 mass/fuel mass	1.184

$$16.12/1.184 = 13.6 \text{ mJ/kg of } O_2$$

Ethylene $C_2 H_4$

Heat of Combustion	47.17 mJ/kg
Ratio O_2 mass/fuel mass	3.422

$$47.17/3.422 = 13.78 \text{ mJ/kg of } O_2$$

Note that13.6 mJ/kg is very close to 13.78 mJ/kg and that both are close to the average of 13.1 mJ/kg (5622 Btu/lb) This happens because ethylene requires about three times more oxygen for complete combustion compared to cellulose..

Thornton's Rule is a key scientific fact used in fire engineering today. Also Thornton's Rule provides a solid, scientific foundation for fighting fires. Not only is the rate of heat release controlled by the amount of oxygen available but also this is a near constant for each unit of oxygen consumed. Now let's consider how Thornton's Rule affects how much water is needed to fight confined structure fires.

Thornton's Rule states that confined spaces of the same volume have the same volume of oxygen available so that the rate of heat release is the same. Larger spaces have more oxygen available and consequently have a greater rate of heat release. The Royer Nelson formula works in exactly the same way. Confined spaces of the same volume require the same amount of water to fill that space full of steam. Larger spaces require larger amount of water to fill larger spaces. So Thornton's Rule and the Royer Nelson formula work hand in hand, since both are based upon the volume of a confined space. Further, the amount of water applied by the Royer Nelson formula is sufficient to absorb all the heat produced by the amount of oxygen in the confined space. This is one of the two scientific facts upon which the Royer Nelson formula is based.

Fog Tactics

Bill Nelson's fundamental principle of fire fighting states that the right amount of water must be applied to a confined fire. To do this a fog nozzle must be capable of doing three things.

- First, the nozzle must be able to vary the flow rate from 30 gpm (113,5 Lpm) to 150 Gpm (576,7 Lpm)
- Second the nozzle must be able to vary the fog pattern from a straight stream to a wide angle short reach stream
- The fog nozzle must be able to shut down immediately.

There are two types of fog nozzles that satisfy these three requirements. One type is an automatic nozzle with a slide type shut off valve with six click (détente) stops on the shut off handle. These stops vary the flow rate from 30 Gpm (113,5 Lpm) to 150 Gpm (576,7 Lpm). The second type is a non-automatic nozzle with a manual volume control ring that varies the flow rate. A ball type shut off valve may be used with this nozzle. Otherwise, the ball type shut off valve cannot be used with a fog nozzle that cannot vary the flow rate. Such a nozzle is restricted to two flow rates—0 flow when shut, or maximum flow when fully open Attempts to flow with the handle partially open results in serious deterioration of the fog stream plus there is no way to determine how much water you are flowing. All of these nozzles are constant flow nozzles, that means that the flow rate does not change with a change in stream width or reach.

There is an art to fighting fires. There is much more involved than just opening a nozzle and pointing it in the general direction of the fire. The following four tasks must be performed in order to make an effective fog attack upon a confined oxygen limited structure fire.

1. Adjust the width of the fog stream (shorten the reach) so that the stream just reaches across the room. We want no splattering off walls or ceiling.
2. Open the nozzle and select the flow to the ideal rate for the size room, 30 Gpm (113,5 Lpm) for 1,000 cubic feet (28,3 cubic meters), and so on.
3. Distribute the water evenly throughout the fire area by rotating the nozzle clockwise inside the room, or by some other means.
4. Shut off the flow immediately upon the disappearance of the flames. Condensed steam appears as steam expands out the windows or door, and upward out of the structure.

If you do these tasks you will perform an effective fog attack in a safe manner that will be successful 100% of the time.

The NFPA reports that in the United States about 75% of all structure fires are in one or two family detached dwellings. Also about the same percentage of structure fires are confined to the room of origin using a single attack line. In view of these facts, every fire department (brigade) should be able to handle your structure fires easily using the water that is carried on your fire trucks. There should be no excuse for suffering a fatality during any of these operations. The combination attack, backed up by the 3D pulse fog attack should guarantee that a structural fire attack can be conducted safely, 100% of the time.

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