Thornton's Rule and Its Consequences
By John D. Wiseman

For effective firefighting, firefighters must have a thorough and accurate knowledge of fire behavior. Fire behavior is defined as what happens in a structure when fire occurs where the only controls are those factors built into the structure itself. Most often, the process of combustion involves the burning of organic solids. These materials may be simple or highly complex compounds with carbon as the principal element. Almost all contain hydrogen. Many contain oxygen, nitrogen, and other elements in smaller amounts.

The products of combustion are heat, water (H_2O is an oxide of hydrogen), and carbon dioxide (CO_2). Incomplete combustion results in the formation of carbon monoxide (CO) and soot- a carbonaceous particle.

The heat of combustion is the amount of heat released by a substance and is measured by megajoules peer kilogram (MJ/kg). A joule is an international Unit (IU) of heat energy. A joule is related to the more familiar calorie, which is not an international unit. A calorie is the amount of heat required to raise the temperature of one gram of water one degree Celsius at 15ºC. One calorie equals 4.183 joules.

A megajoule is 1,000,000; and a kilogram is 1,000 grams. A kilogram is equal to the mass of one liter of water in air at 4ºC

The heat of combustion supposes complete combustion. Since this is rarely the case in actual fires, the heat of combustion represents the upper limit of the heat produced by substances under normal conditions. It is symbolized by

$$\Delta h_c^u$$

c
Which is read, "The upper heat of combustion" .A lower level heat of combustion is also defined, and its symbol is

$$\Delta h_c^l$$

The lower heat of combustion is the heat produced under normal conditions.

The tables in the NFPA (National Fire Protection Association) Handbook (Appendix A of the 17th Edition) contain information about the heat of combustion and other data about three classes of substances. Here are some examples from each of the three classes

(1) **Pure and Simple Substances-Heat of Combustion**

	MJ/kg	Composition
Benzene	41.83	$C_6 H_6$
Carbon	32.80	C
Cellulose	17.47	$C_6H_{10}O_5$
Ethanol	29.67	$C_2 H_6 O$
Hydrogen	141.79	H
Methanol	22.68	CH_4O
Nitroglycerin	6.82	$C_3H_5 N_3 O_9$
Propane	50.35	$C_3 H_8$
Sucrose	16,49	$C_{12}H_{22}O_{11}$

(2) **Plastics – Heat of Combustion**

	MJ/kg	Composition
Cellulose Acetate	18.88	$C_{12}H_{18}O_8$
Nylon 6	30.1 – 31.7	$C_6 H_{11}NO$
Polyethylene	46.2 – 46.5	$C_2 H_4$
Polystyrene	41.4 – 42.5	$C_8 H_8$
Polyurethane	23.9	$C_{63}H_{71}NO_{21}$
Vinyl Acetate	24.18	$C_4 H_6 O_2$

(3) **Some Common Substances, Heat of Combustion**

	MJ/kg
Celluloid	17.5 – 20.6
Cotton	16.5 – 20.4
Gasoline	46.8
Leather	18.2 – 19.8
Paper (brown)	16.3 – 17.9
Rayon (fiber)	13.6 – 19.5
Rubber (buna N)	34.7 – 35.6
Straw	15.6
Wood (beech)	20.0

In general, the heat of combustion for plastics in many cases is nearly twice tht for "ordinary" combustibles.

Both classes of substances are solid organic compounds, of which there are two kinds: (1) hydrocarbon-based materials, and (2) cellulose-based materials. Plastics belong to the first kind, while most common substances belong to the second kind. Both kinds contain carbon and hydrogen atoms. However, cellulose materials are based on a partially oxidized carbon unit, hence, they consume less oxygen and produce less heat.

So, one important conclusion from the tables is that hydrocarbon-based materials (plastics) consume 50% more oxygen and thus produce 50% more heat than cellulose based materials. In a pound-for-pound comparison, hydrocarbons produce twice as much heat as cellulosics. This generalization in recent years has been used to justify the use of 13/4 and two-inch attack lines in fire fighting. The rationale is that fires now produce more heat than several decades ago, hence, the need for greater flows.

However, other data in the table should be considered before making any conclusions. Two of the tables contain the value of the stoichiometric oxygen-fuel mass ratio. This number is the ratio of the molecular mass of oxygen and fuel as they combine in the combustion process. The symbol is "r_o". Stoichiometric refers to the combustion process. Then, one additional step is taken the heat of combustion for each substance is divided by r_o, which gives the ratio of the heat of combustion per kilogram of oxygen consumed. The symbol for the ratio is:

$$\frac{\Delta h_c^{1}}{r_o} \quad \text{for } O_2$$

where O_2 is molecular oxygen resent in air.

The following table lists this ratio for pure and simple substances and the plastics previously listed. There is no data for common substances.

(1) **Pure and Simple Substances**

Benzene	13.06
Carbon	12.31
Cellulose	13.61
Ethanol	12.88
Hydrogen	16.35
Methanol	13.29
Nitroglycerin	unstable
Propane	12.78
Sucrose	13.44

(2) Plastics

Cellulose Acetate	14.67
Nylon 6	12.30
Polyethylene	12.63
Polystyrene	12.93
Polyurethane	13.66

Vinyl Acetate	13.54

This data is quite remarkable. There is no doubt about the conclusion drawn by Dr. Vytenis Babrauskas, the author of these tables, when he states:

"Recently, however, increasing engineering use is made of the observation that the heat of combustion per kilogram of oxygen consumed is nearly constant for most organic fuels. It can be shown that the value of

$$\frac{\Delta h_c^1}{r_o} = 13.1 \text{ /kg for } O_2$$

is near constant." [1]

Dr. Frederick B. Clarke reinforces this conclusion in his article ,"Fire Hazards of Materials, An Overview", when he states

"Examination of the heat of combustion tables in Appendix A will show that, while the heat of combustion is quite different for different organic materials, the heat produced per equivalent of oxygen consumed is the same within about 10 percent, -+ 5. This fact, sometimes called Thornton's Rule", allows one to use oxygen consumption as a reasonable measure of the heat produced by a burning organic material."[2]

Thus we have arrived at Thornton's Rule. I will examine the consequences of Thornton's Rule for oxygen limited fires (typical ventilation-controlled compartment fires). John A. Campbell, in his article "Confinement of Fires in Buildings," states:

"Considerable ventilating area is required for a fully developed fire to burn at a fuel-surface controlled rate. For example, over one-fourth of the wall area would have to be open in a 20 x 20-ft room (6.1 m x 6.1 m) with an 8-ft ceiling (2.4 m and an exposed combustible surface of 800 ft^2 (74.3m) of ordinary combustibles. Many, if not most building fires will be ventilation controlled at least during the period of time in which containment is a consideration".[3]

Thus, firefighters confront oxygen-limited fires all the time. Since 73 % of all structure fires and 75.5% of all house fires are confined to the room of origin, the consequences of Thornton's Rule are enormous.

In oxygen-limited fires, the type of organic material burning is irrelevant since the amount of heat released is constant for a given amount of oxygen consumed. Therefore, the widespread use of plastics does not indicate a need for greater fire flows than in years past. In oxygen-limited fires, cellulose-based materials release just as much heat as hydrocarbon-based materials per unit of oxygen consumed.

Consequences of Thornton's Rule

This is the first consequence of Thornton's Rule, and it contradicts a widespread belief held by many in the fire service.

The second consequence of Thornton's Rule is that it validates the Iowa Rate-of-flow formula. The Iowa formula was discovered in the 1950s by Keith Royer and Floyd W. Nelson at Iowa State University. The formula is:

$$\text{NFF (30 sec)} = \frac{L \times W \times H}{100}$$

Where NFF = the rate-of-flow in gpm, L = length, W = width, and H = height, and their product equals the volume of a confined space in cubic feet.

The denominator is derived from the expansion ratio of water to steam at 212° F which is 227 cubic feet per gallon. In the experiments conducted at Iowa State, it was determined that water need by applied for no more than 30 seconds. The number 227 was rounded down to 200 to allow for a 90% conversion of water to steam. So instead of one gallon flowing for one minute, only ½ gallon flows for 30 seconds creating 100 cubic feet of steam. The time of 30 seconds should always be included in this formula.

The validity of the Iowa formula rests on two facts. Keith Royer has explained how the formula emerged in this way

"1. Study of expansion ratios of water to steam indicated that one gallon of water will produce, with a margin of safety, 200 cubic feet of steam.

2. Study of heat production in relation to oxygen also indicates that as the conversion of to steam, one gallon of water will absorb, with a margin of safety, all the heat that can be produced with the oxygen available in 200 cubic feet of normal air. These two factors lead to the formula: cubic area in feet divided by 200 equals the required gallonage of water for control of a specific area involved in fire."[4]

Note the relevance of Thornton's Rule to (2).

The preceding gallonage formula stated in symbols is:

$$\text{Gal} = \frac{\text{Vol}}{200}$$

Where Gal = the number of gallons of water, and Vol = the volume of the confined space. It is worth noting that with a 90% rate of conversion of water to steam only five gallons of water are needed to produce 1,000 cubic feet of steam which will control a small room fire. Also, only 100 gallons of water are needed for a fully involved average-size house (20,000 cubic feet). However, this is not easy to do because of the following constraints that restrict the use of fog attack.

(1) The water must be distributed properly—that is, evenly throughout the fire area. This requires about 10 seconds which constitutes the minimum restraint.
(2) The fire must be confined (i.e. ceiling or roof intact) so that the steam blanket will hold for at least two minutes. This limit constitutes the absolute maximum constraint.
(3) Within the lower and ujpper constraints, if the right amount of water is exceeded, then an effective fire attack is disrupted. This constitutes a variable constraint caused by too great a rate-of-flow or by application for too long a time..

If constraint (3) is exceeded, the result is thermal imbalance. Thermal balance exists before a fire attack is made and returns quickly if the right amount of water is used. Thermal imbalance results in extreme turbulence, a disruption of the even layering and distribution of temperatures and blocking of the smooth flow of energy into and out of the fire. Thermal imbalance will delay overhaul, prevent the extinguishment of all of the fire, and may even blow or spread products of combustion into other areas of the structure. None of this happens if the right amount of water is used. The Iowa rate-of-flow formula gives you the right amount of water.

Now we have arrived at the third consequence of Thornton's Rule. Using too much water disrupts an effective fire attack on confined fires. Let's find out how much is too much. Starting with the gallonage formula:

$$(1)\quad \text{Gal} = \frac{\text{Vol}}{200}$$

The right amount of water can be applied at different rates depending on time—that is, how long the needed fire flow is applied. This relationship is expressed by the following equation.

$$(2)\quad \text{NFF} \times t = \text{Gal}$$

Where NFF = needed fire flow in gpm, t = time in minutes or fraction of a minute (please note this), and Gal = a constant for a given size fire, the number of gallons needed for fire control.

Since the volume of water needed is constant for a given size fire, increasing the flow decreases the time needed for fire control. Likewise, decreasing the flow increases the time needed for control. For example, a 2,000 cubic-foot fire requires 10 gallons of water. If the flow is 60 gpm, then

$$60 \times 1/6 = 10$$

where 1/6 is a fraction of a minute, or 10 seconds. If the flow is 60 gpm, then

$$69 \times 1/6 = 10$$

where 1/6 is a fraction of a minute, or 10 seconds. If the flow is 30 gpm, then

$$30 \times 1/3 = 10$$

Where 1/3 is 20 seconds

Combining the two preceding equations by eliminating Gal from (1) and (2) gives the following equation

$$(3)\quad NFF \times t = \frac{Vol}{200}$$

Now, suppose that there is a small room, 10 x 12 x 8 which is approximately 1,000 cubic feet, and that this room is fully involved with fire. Suppose further that an attack is made on the fire with 11/2 hose flowing 100 gpm. Substituting 100 into equation (3)

$$100 \times t = \frac{1{,}000}{200}$$

Dividing both sides of this equation by 100 gives:.

$$t = \frac{1{,}000}{20{,}000}$$

$$\text{Or} \quad t = 1/20$$

which is equal to three seconds. Therefore, it is not possible to properly execute a combination attack that would distribute water evenly throughout the fire area. The 11/2 inch line flows too much water since the attack falls outside the minimum constraint of 10 seconds.

The results are even worse with 13/4 or two-inch attack lines. Remember that at least 75 % of all structure fires are confined to the room of origin. The conclusion then is that firefighters would have to be extremely careful in using present-day attack lines to avoid using too much water, thereby creating thermal imbalance.

I have one suggestion. I hesitate to recommend going back to booster lines even though the 30 gpm controls the 1,000 cubic-foot fire in 10 seconds. Instead, I suggest opening the fog nozzle only half-way for smaller fires. Halfway on a 11/2 inch lines means flowing 50 gpm. This line should be closed down more that this for the small 1,000 cubic-foot size fire.

For larger fires involving an entire house, proper distribution requires multiple attack lines. The most effective attack occurs when water is applied simultaneously to all rooms of the structure. This calls for small attack lines instead of larger ones. The reader should do some calculations with (3) to see what is required to properly distribute water for such fires.