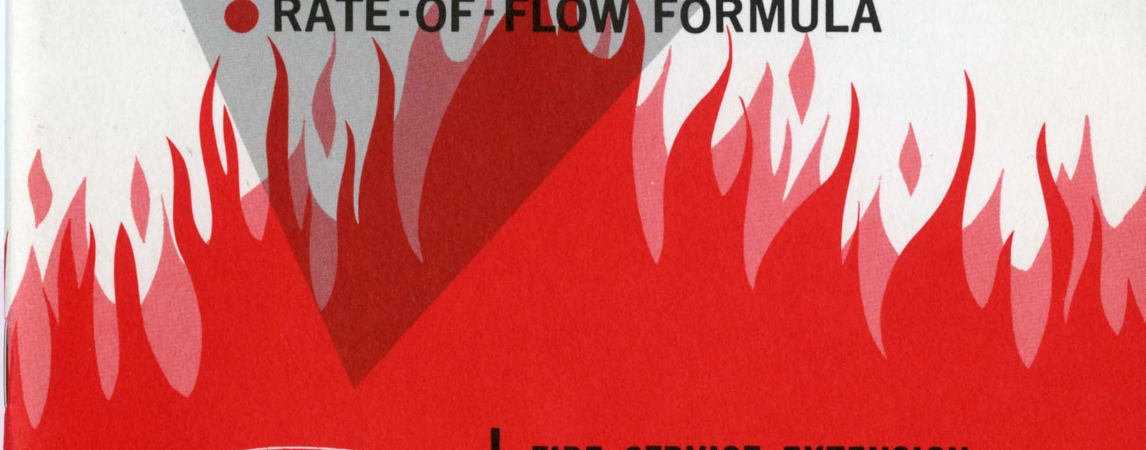
IOWA STATE UNIVERSITY BULLETIN

WATER FOR FIRE FIGHTING

RATE-OF-FLOW FORMULA



FIRE SERVICE EXTENSION
ENGINEERING EXTENSION
IOWA STATE UNIVERSITY
of Science and Technology

FOREWORD

During World War II many of the people involved in fire fighting and fire protection had to find more efficient methods of coping with fire problems.

The U.S. Coast Guard and the Navy carried out experimental and research projects which provided the impetus for further work by civilian groups after World War II.

In 1950 a national committee was formed known as "Exploratory Committee on the Application of Water." This committee attempted several experiments with varying degrees of success. Its work was limited because of a lack of financial resources. The committee work also provided additional impetus for other groups and educational institutions to become involved in further research.

Iowa State University, through its Fire Service Extension program, started research in application of water early in 1952. Close coordination was established with research groups in other countries. The British Fire Research Station was very helpful, as well as Canada, Germany, Japan and Australia.

The main objective of this bulletin is to record the "rate of flow" formula for fire control, which evolved from the fire research efforts here at Iowa State University.

This formula, with the data which supports it, has become a very useful strategic and tactical tool in planning for fire control.

Keith Royer

Iowa State University
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WATER FOR FIRE FIGHTING
(Rate-of-Flow Formula)

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Two important questions which seem uppermost in the minds of many firemen are: At a given fire how much water do we need and how should the water be used? Lacking even a suggested formula for determining flow rates for a specific fire, many fire officers have developed some method of their own for "guesstimating" the required flow. The big problem is that it is generally so vague that few officers can explain just how this is done. As a result there is no way to pass this information on to a new fireman who needs and wants the information. Hence he must wait until he has had enough actual experience to develop the means to answer this question to his own satisfaction.

After several years, and hundreds of experiments, a rate-of-flow formula has evolved which seems to be a practical answer to the first question. This is based on the following data:

1. Study of expansion ratios of water to steam indicates 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 in the conversion of water to steam, one gallon of water will absorb, with a margin of safety, all of 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.

Experiments have shown that this formula was sufficient as a rule of thumb for the required amount of water, but it still did not establish the necessary rate of flow.

Analysis of time-temperature curves prepared from hundreds of test fires conducted by Iowa State University in Iowa, indicates that results are best when rate of flow is sufficient to introduce the required amount of water into the area of involvement in 30 seconds.

This led to a rule-of-thumb rate-of-flow formula: GPM equals cubic area in feet divided by 100.

The cubic feet in the formula refers to a given cubic area involved in fire. The formula gives an ideal rate of flow for a given fire situation. Its successful application definitely requires prefire planning. The following quotation [1] is of interest at this point:

"Developing a formula for water flow for fire extinguishment is not new. As early as 1925, Engineer Stanzig in Vienna developed a procedure for determining water flow for given fire test situations. Stanzig's experiments and experiences were further substantiated by Chief Fossoult of Anderlecht, Belgium, and later by Chief Folke of Fredericksburg, Denmark.

"Elaborations of the Danish experiments have shown that a formula may be worked out for a minimum superior jet as a function of time. This formula holds only (1) when the scene of the fire is not too large for the jet to control the entire area and (2) if the fire is still principally in the combustion stage without large amounts of glowing coals or other hot substances.

"In other words, in the case of many fires reached in the early (ignition and combustion) stages, it is deduced from the plotted figures arrived at that $Q = t \quad 100$.

"Q is the liters per minute per square meter of burning surface, and is in minutes. (The formula, with Q as U.S. gallons per minute per square foot would be roughly $Q = 5/4000$.)

"In practice this means that ½ liter per minute per square meter (roughly ½ quart per square yard) of floor area will produce a fire stream superior to an ordinary fire. If there is already much heat at the scene of the fire, 5 liters per minute per square meter (roughly 1 gallon per square yard) will, as a rule, still be superior.

"The results of the Danish experiments conform to the views of Stanzig. The 'standard' jet or stream of 500 liters per minute (130 U.S. gallons) has thus proved to be rather large. In the majority of cases, 200 liters per minute per 100 square meters (about 50 U.S. gallons per minute per 1,000 square feet) would suffice. Often even half this amount would be sufficient."

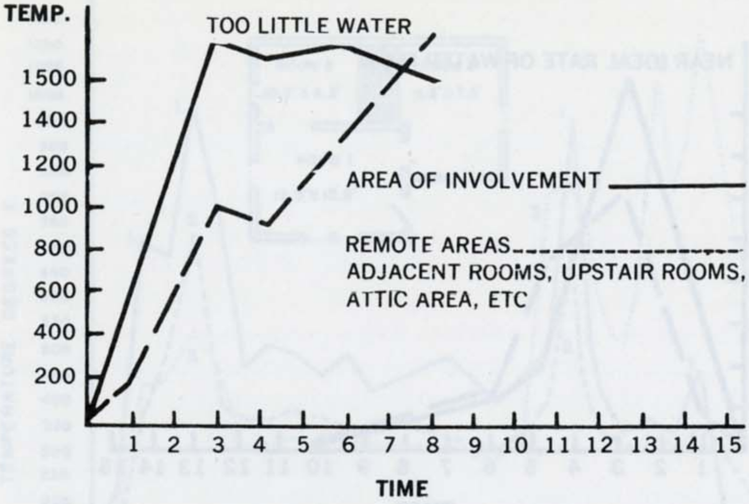
While test fires are seldom lost, time-temperature curves of experimental fires reveal many cases where trouble was encountered either in knockdown or overhaul. The following composite graphs were prepared from the study of many time-temperature curves of actual fires where the formula was tested.

When the rate of flow is too small in relation to heat production and accumulation, there may be only a slight temporary reduction in temperatures in the fire area. Rate of heat production in remote areas may be increased. This graph (fig. 1) would also be typical of circumstances where the rate of flow was ideal but proper distribution was not made.

When the rate of flow is substantially greater than ideal, the temperature drop in the fire area will be very rapid, steam pro-

[1] *NFPA Quarterly, April 1947, Vol. 40, No. 4, "Deductions from Research on the Use of Water," H. Adeler, Chemical Engineer, Danish Fire Protection Committee.*

Fig. 1. Average time-temperature curve with too little water



duction will be limited, and heat production will increase in remote areas. Smoke from smoldering fuels will hang in the cool atmosphere of the area, complicating overhaul, sometimes to the extent that spot fires will come back as illustrated by fig. 2. This will also delay control of fires in remote areas, especially if the only approach to these areas is through the area of first involvement.

The above conditions can also be created when rate of flow is ideal but application is continued beyond the point where the fire in the area of application blacks out.

Fig. 2. Average time-temperature curve with too much water.

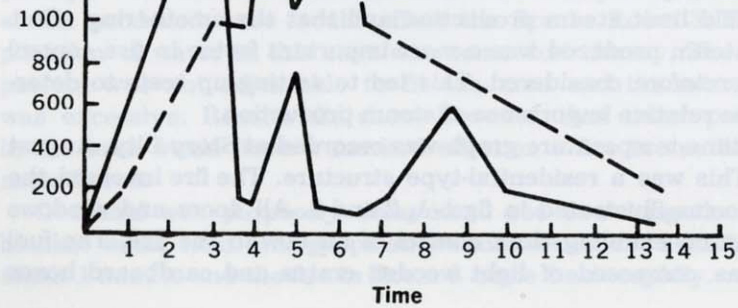
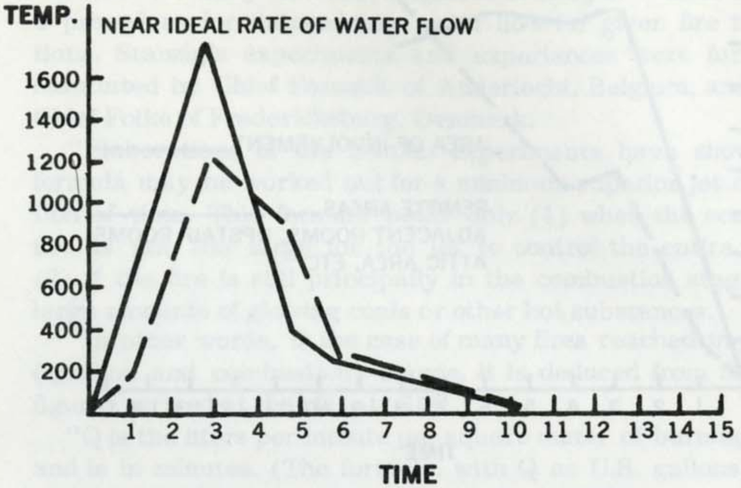


Fig. 3. Average time-temperature curve with ideal amount of water, properly distributed.



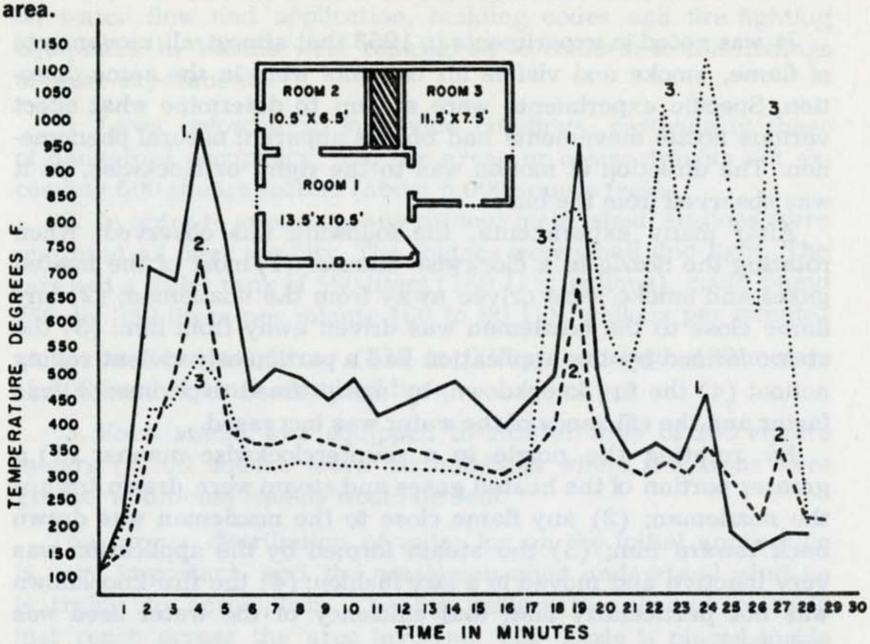
When rate of flow is ideal, results will be best. Distribution is proper and the flow is stopped when the fire blacks out (usually 20 to 30 seconds). The area will be filled with steam, and temperatures will continue to fall after application is stopped. Steam will flow into remote areas where heat or fire may have spread and temporarily suspend heat production in these areas. Temperatures in the area of involvement will be relatively high—200 to 400 degrees at ceiling level—and smoke in the area will lift rapidly. Overhaul crews will be able to move in to extinguish spot fires in both the main area and the remote areas.

Examinations of these graphs indicate that results were less than ideal when the rate of flow was either above or below the ideal rate. This posed the additional question as to why excessive application of water would complicate fire control.

The only possible answer seemed to be that excessive application would limit steam production and that the smothering effect of the steam produced was a more important factor in fire control than heretofore considered. This led to setting up tests to determine the relative importance of steam production.

The time-temperature graph was recorded at Story City, August 1954. This was a residential-type structure. The fire involved the three rooms illustrated in figs. 1, 2 and 3. All doors and windows were intact, enabling close control of air flow to the fire. The fuel load was composed of light wooden crates and cardboard boxes

Fig. 4. Typical time-temperature curve showing the effect of air flow into fire area.



and was somewhat heavier than would be encountered in the average residence.

The fire was ignited in Rooms 1 and 3 simultaneously and spread into Room 2. The front door was left open for the first 2 minutes as the men who had ignited the fire watched it build up from the doorway. The temporary leveling off of temperature rise between the second and third minute was a period during which the fire was apparently forced to set up new patterns of air flow when the front door was closed. When the available oxygen in the area was consumed at the end of 4 minutes, heat production slowed and temperatures dropped rapidly. During the next 12 minutes temperatures rose and fell as the fire breathed.

At the end of 17 minutes the front door was opened slowly to allow temperatures to build up in the area. At 19 minutes, application was made into Room 1 in an attempt to determine if steam produced here would affect the fire in Room 3. The application of water in this case was somewhat clumsy. The nozzle pattern was not adjustable to fit the area and the rate of flow was excessive. Results did show, however, that steam produced in one area would have a marked effect on a fire in another connected area.

Overhaul was purposely delayed to see how long the steam blanket would hold. The graph shows that the steam held for only about 1 minute and the fire in Room 3 came back rapidly.

APPLICATION OF IDEAL RATE OF FLOW

It was noted in experiments in 1953 that almost all movements of flame, smoke and visible air currents were in the same direction. Specific experiments were set up to determine what effect various nozzle movements had on this apparent natural phenomenon. The direction of motion was to the right, or clockwise, as it was observed from the base.

After many experiments, the following was observed: When rotating the nozzle in a clockwise manner (1) most of the heated gases and smoke were driven away from the nozzleman; (2) any flame close to the nozzleman was driven away from him; (3) the steam formed by the application had a particularly violent rolling action; (4) the fire knockdown, by many timed experiments, was faster and the efficiency of the water was increased.

By rotating the nozzle in a counterclockwise manner (1) a greater portion of the heated gases and steam were drawn toward the nozzleman; (2) any flame close to the nozzleman was drawn back toward him; (3) the steam formed by the application was very inactive and moved in a lazy fashion; (4) the fire knockdown was not particularly fast, and efficiency of the water used was reduced.

Several attempts have been made by qualified people to explain this phenomenon which occurs with the clockwise rotation of the nozzle into highly heated areas. At this writing no satisfactory answer or explanation has been provided. However, there are strong indications that it involves natural forces which are at work on the molecule. It is known and proven by experiments that the previously mentioned results are accomplished by the clockwise rotation of the nozzle. This rotation should be made following the contour of the area, striking as much of the perimeter as possible with the outer surface of the fog stream. This rotation should be as violent as it is possible for the nozzleman to make it.[2]

The information on nozzle manipulation, like rate of water flow, is not new. Chief Officer F. Folke, Fredericksburg, Denmark, in his paper "Experiments in Fire Extinguishment"[3] stated:

"Experiments as early as 1930, also, uncovered the importance of nozzle manipulation. Stanzig concluded a high nozzle pressure was still considered important—9 to 12 atmospheres (130 to 175 pounds). This was to obtain good distribution of the water from the ricochet effects. Good distribution was aimed at by very energetic movement of the nozzle pipes. Stanzig said, 'The nozzle pipe movement must be just as violent as bayonet fighting.'

"Following this principle, in Vienna it was customary to run out a few light hose lines quickly and after a few minutes the fire

2 *NFPA Quarterly, Oct. 1937, Vol. 31, No. 2.*

3 *See footnote 1, page 4.*

would be knocked down in most cases. As a result of this research on water flow and application, building codes and fire fighting equipment in Vienna were redesigned to conform to the findings of these experiments:

"1. Laws enforced to subdivide buildings, particularly those of dangerous occupancy, into fire areas or compartments not exceeding 500 square meters (about 5,000 square feet).

"2. In order to assure speedy turnout many small stations were scattered all over the city. The engines were small and light. The cars had a water tank of 560 liters (150 U.S. gallons), could pump 250 to 350 liters per minute (60 to 90 U.S. gallons per minute) at 25 to 20 atmospheres (375 to 300 psi) through 400 meters (1,300 feet) of 2-inch standard hose.

"3. Each squad was equipped to master fires of 250 square meters (2,700 square feet). To buildings where fire areas were greater additional squads would be sent."

The proper distribution of water fog on the initial application is very important, and the nozzleman must understand what he is trying to accomplish. The fog pattern is adjusted so it will just reach across the area involved. The nozzle is placed inside the area and rotated—following the contour of the area—striking as much of the perimeter of the area as possible with the outer surface of the fog stream: across the ceiling, down the side, across the floor, up the side, across the ceiling, etc. This rotation is as violent as it is possible for the nozzleman to make it. In placing the nozzle inside the area, it should be inside the window or other opening about an arm's length. In order to do this the nozzleman must have gloves, helmet and protective coat.

The purpose of rotating the nozzle is to obtain stream production over as much of the area as quickly as possible. When the water strikes any of the heated material in the room momentarily, it creates a steam blanket. If nozzle rotation is rapid enough, this steam blanket will hold until the nozzle has a chance to get around to that spot again. If the rotation is too slow, this steam blanket will not hold and the fire which has been knocked down will build up before the nozzle passes its way again.

In addition to the amount of water flow and manipulation of the nozzle, air flow into a given fire area is an important consideration. The amount of heat that is released by burning different types of fuels varies. This characteristic of fuel is referred to as its calorific value. In the fire service the fuels can be divided into two general classes with average calorific values: Class A fuels—ordinary combustibles—fuels that burn and leave glowing coals. This group has an average calorific value of 8,000 b.t.u.[4] per pound. Class B fuels burn primarily on or above the surface and leave no glowing coals. For this group we use an average calorific value of 16,000 b.t.u. per pound.

The above figures are not of too much value to the fireman in thinking of fire extinguishment. They provide a means of figuring the amount of heat there will be if the contents of a building are entirely burned, and are of interest to men who design buildings to withstand fire.

The fireman is more interested in the amount of heat that is being produced when he makes his attack and the fact that the oxygen supply to a fire does more to set limits on heat production than the amount of fuel available.

It has been determined that with most common fuels the union of 1 cubic foot of oxygen with a fuel will produce 535 b.t.u. If we break this fact down to a rule-of-thumb figure that can be used by firemen, we have the following: Approximately 7 percent of normal air is oxygen that can be used by a fire. Normal air contains 21 percent oxygen, and when this is lowered to 14 percent, burning is arrested. Seven percent of 535 is 37 b.t.u., which is the amount of heat that can be produced by consuming the available oxygen. One gallon of water can absorb 9,330 b.t.u. If we divide 9,330 by 37, we find that 1 gallon of water should absorb all the heat that 252 cubic feet of ordinary air will produce. As a rule of thumb it can then be said that 1 gallon of water will absorb all the heat that 200 cubic feet of air can produce.

The above would be true if no air were allowed to enter or leave a given fire area. However, it must be remembered that as air flows into a fire area, heated gases and products of combustion must escape from that fire area. This coupled with the heat loss by conduction through the walls will mean that the total amount of heat in the area will remain fairly constant and very close to an estimate that can be arrived at by using the above figures. This will remain true on a varying scale up to the time that large amounts of red-hot carbonaceous material accumulate in the fire area.

When a fire is partially ventilated it is difficult to judge the degree of ventilation. A rule-of-thumb formula needs to be developed for estimating the degree of ventilation on any given fire. This would be especially helpful in making comparisons of fire tests and experiments. It should be noted that the United Kingdom through its Fire Research Station is currently conducting experiments and tests in this area.

4 *One b.t.u. is the quantity of heat required to raise the temperature of 1 pound of water 1 degree F.*

HEAT, ITS PRODUCTION AND CHARACTERISTICS

From the beginning of organized fire fighting it was recognized that water was the most plentiful, efficient and economical extinguishing agent that could be used in day-to-day operations. However, it has only been in recent years that more has been learned from basic and applied research that enables the fire fighter to understand how he can better use the water available. In order that he may get the maximum use from water in fire-fighting operations, *it is necessary to understand thoroughly the combustion process and fire behavior in general* as developed from this research.

There are several questions, the answers to which the fire fighter should know thoroughly if he is to utilize the available water to a maximum degree of efficiency. These are: *What is heat? How is heat measured? How does it flow? Where does it come from? How much of it is produced at a fire?*

Heat is a form of energy evidenced by the movement or vibrations of the molecules of a substance. In thinking about heat measurement, think about the vibrations of the molecules. How intense is the vibration and how large an area of the molecules of the substance is in vibration? The intensity of the vibrations is measured in degrees of heat, usually Fahrenheit or centigrade. The amount of heat or the intensity and the area of vibration taken together is measured in b.t.u.'s (British thermal units). One b.t.u. is the amount of heat necessary to raise the temperature of 1 pound of water 1°F. (measured at 60°F.).

Amounts of heat are also measured in other units similar to the b.t.u. A calorie is the amount of heat necessary to raise 1 gram of water 1°C (measured at 15°C). This same calorie is also used as a measurement in the amount of potential energy in food. Two hundred fifty-two calories equals 1 b.t.u.

Many times reference is made to the calorific value of combustible materials. The fire protection engineer when determining the fuel loading of the building will take into account the total weight of combustible materials and then determine what the total b.t.u. content of these fuels is. The average calorific value of solid combustibles is approximately 8,000 b.t.u. per pound. With most of the flammable liquids, an average of 16,000 b.t.u. per pound is used. Of more specific interest to the fire fighter rather than the total fuel load, is *the rate at which this heat energy is being released during an actual fire.* This will be dealt with more fully under the section "Amounts of Heat Produced in Fires."

HEAT FLOW CHARACTERISTICS

With a temperature differential, heat flows from hot to cold. Heat flows or transfers from one body to another in three different ways:

1. *Conduction.* Heat travels by conduction through solids or between solids in contact with each other. Think of heat as the vibration of the molecules, and it is easy to visualize how heat flows in a solid. The rate of conduction will depend on the temperature differential and the molecular structure of the solid.

2. *Convection.* Heat moves from one particle to another, but the particles themselves are in circulation. Liquids and gases being heated tend to circulate, thus spreading the heat.

3. *Radiation.* Heat energy is radiated from a hot body to a cold body. Light is a visible form of heat radiation. The initial heat of combustion is released primarily as radiant heat. It is interesting to note that heat traveling by conduction or radiation makes little distinction between up or down, while heat flowing by convection always tends to flow upward.

Heat travels by convection in liquids and gases. The fire service is most concerned with the convection of heated gases. As a gas is heated, the vibration or movement of each individual molecule becomes more and more violent. Collision with its neighboring molecules becomes more frequent and more forceful so that each individual molecule forces its neighbors farther and farther away, causing the heated gas to expand. When a given amount of gas expands, it occupies more space and the amount of gas in that space will weigh less than a corresponding amount of gas at a lower temperature would in the same space. Thus, the heavier gas settles downward, forcing the lighter gas upward. In structural fires, as the cooler air settles to the lower levels, the heat tends to be the greatest at the ceiling level.

In some fires we may have 1,000° to 1,500°F. at ceiling level and perhaps only 150° to 200°F. at floor level. These temperature differences will be greatest when a structure is filled with smoke or steam because the smoke and steam act as a shield against the radiated heat. In the flame-spread stage of a fire, the air may be quite clear, making it easier for heat to travel by radiation. Because heat traveling by radiation makes no distinction between up and down, there is less difference between floor and ceiling temperatures.

How is this heat released? Here we need to look at the combustion process. Combustion is a chemical reaction that results from the union of a fuel with oxygen, liberating heat energy. Flame is visible light energy liberated by the reaction.

While there are a great many of the 92 natural elements that will burn, to understand combustion we need to consider only three: hydrogen, carbon and oxygen. Most of the fuels encountered in ordinary fire fighting will be compounds of hydrogen (H), carbon (C), and oxygen (O). For example:

Natural gas, CH_4 (1 atom of carbon, 4 atoms of hydrogen chemically bonded)

Gasoline, C_5H_{12} to C_9H_{20}

Kerosene, $C_{10}H_{22}$ to $C_{15}H_{32}$

Sugar, $C_{12}H_{22}O_{11}$

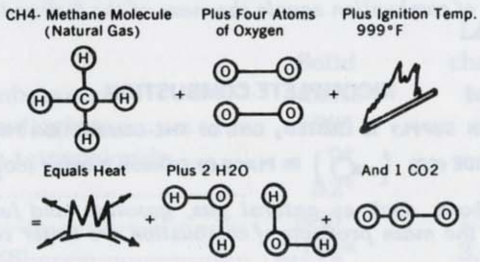
Most of the ordinary fuels that we encounter in the fire service are mixtures. Wood is made up of a cellulose ($C_6H_{10}O_5$) or lignite in combination with various resins and aromatic substances and some free carbon. For illustration purposes, the fuel content of average wood can be taken as $C_6H_{10}O_5$.

It is helpful in understanding fire to study the combustion of one natural gas molecule as illustrated in fig. 5.

To understand the combustion process it is important to realize that in the union of a fuel with oxygen, which is fire, none of the atoms are lost or destroyed. The products of combustion will weigh almost exactly the same as the fuel and oxygen that went into the process. The very small amount of weight lost with the release of heat in the combustion process is not of interest to the fire fighter. Certain elements have a greater affinity for oxygen than do others. For example, hydrogen's affinity for oxygen at ordinary combustion temperatures is greater than that of carbon; therefore, when oxygen atoms are limited, the hydrogen atoms will unite with the oxygen atoms before the carbon.

In fig. 5, if there were only three oxygen atoms present, the carbon dioxide could not have formed. Instead there would be

Fig. 5. Combustion process of one molecule of methane gas.



carbon monoxide (CO). Other hydrocarbon molecules such as those of gasoline or wood are more complex, but the basic principle of combustion is the same. Oxygen unites with hydrogen or carbon, gives off heat, and forms water and carbon dioxide.

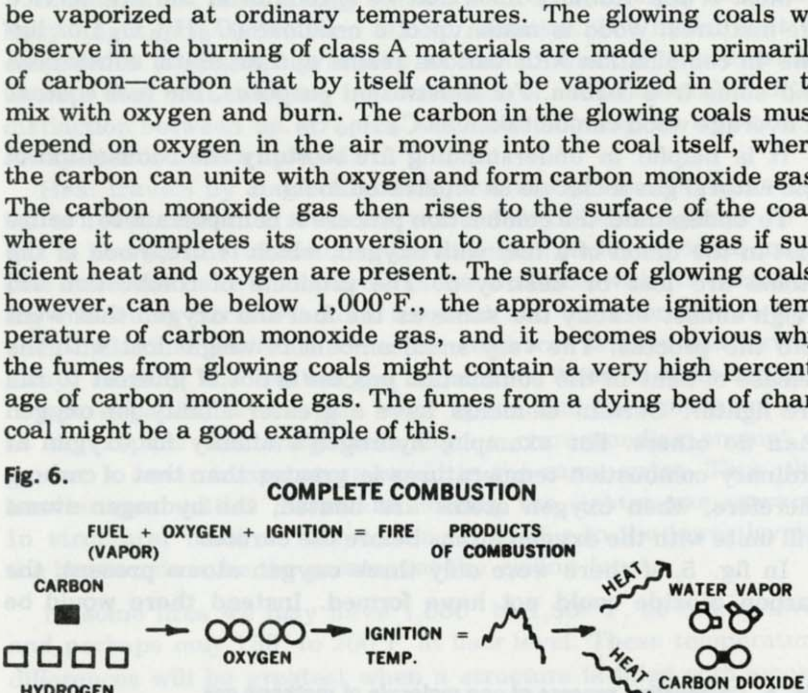
For example, using the simplified formula for wood with proper ignition temperature, the following reaction takes place:

$$C_6H_{10} + 6O_2 = 6CO_2 + 5H_2O + Heat$$

Wood is made up primarily of carbon and hydrogen but contains considerable amounts of free carbon. That is carbon not bonded with any other element. Carbon bonded with another element such as hydrogen in natural gas can be vaporized and can be driven to the surface of the wood, where it combines with oxygen and undergoes combustion. Free carbon, however, cannot be vaporized at ordinary temperatures. The glowing coals we observe in the burning of class A materials are made up primarily of carbon—carbon that by itself cannot be vaporized in order to mix with oxygen and burn. The carbon in the glowing coals must depend on oxygen in the air moving into the coal itself, where the carbon can unite with oxygen and form carbon monoxide gas. The carbon monoxide gas then rises to the surface of the coal, where it completes its conversion to carbon dioxide gas if sufficient heat and oxygen are present. The surface of glowing coals, however, can be below 1,000°F., the approximate ignition temperature of carbon monoxide gas, and it becomes obvious why the fumes from glowing coals might contain a very high percentage of carbon monoxide gas. The fumes from a dying bed of charcoal might be a good example of this.

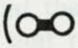
Fig. 6.

COMPLETE COMBUSTION



Matter is not destroyed or lost in the combustion process. The mass of the products of combustion equals the mass of the fuel and oxygen—no more, no less.

INCOMPLETE COMBUSTION

WHEN THE OXYGEN SUPPLY IS LIMITED, ONE OF THE COMBUSTION PRODUCTS WILL BE CARBON MONOXIDE (CO) () IN PLACE OF CARBON DIOXIDE (CO_2). ()

When hydrocarbons, such as natural gas, gasoline, and fuels (such as wood) burn, the main products of combustion are water vapor and carbon dioxide.

AMOUNTS OF HEAT PRODUCED IN FIRES

The amount of oxygen available to a fire governs the heat that can be produced with ordinary fuels regardless of their nature. One cubic foot of oxygen united with fuel in a fire will produce 535 b.t.u. Normal air contains 21 percent oxygen. When the oxygen content of air drops below approximately 14 percent, flame production is arrested, although some smoldering combustion in glowing coals will continue below this point. For practical purposes, subtracting 14 from 21 leaves only 7 percent oxygen per cubic foot of air available for the ordinary fire. Since 1 cubic foot of oxygen, in combination with a fuel, will release 535 b.t.u., 1 cubic foot of ordinary air will produce only 7 percent of 535 or 37 b.t.u.

A room 6 by 6 by 6 feet would contain about 200 cubic feet. This amount of air would produce 7,400 (200 x 37) b.t.u. If additional air flowed into this room during a fire to produce more b.t.u., hot air would have to leave the room and would carry away some of this heat. In addition, the area would lose heat constantly as a result of conduction and radiation. Consequently the heat remaining in the area in the early stages of a fire will remain near the original 7,400-b.t.u. figure. The heating of heavy noncombustible structural materials or the accumulation of large amounts of glowing coals may increase the total accumulated b.t.u. in the latter stages of the fire.

THE THREE STATES OF MATTER

Matter occurs in three states—solid, liquid and gaseous—all affected by heat. Solids have definite volume and definite shape. Liquids have definite volume, but no shape. They assume the shape of whatever contains them. Gases have neither definite volume nor definite shape. They expand and take the shape and volume of any vessel in which they may be confined; unconfined, they expand indefinitely. Most all elements and compounds can exist in any one of the three states. The change from one state to another is primarily a physical change. As heat is applied to a solid, it melts; as more heat is applied, the liquid turns to a gas.

Substance	Solid melts	Liquid changes to gas
Carbon dioxide	-109°	-110°
Carbon tetrachloride	- 9°	170°
Water	32°	212°
Zinc	680°	1,900°
Cast iron	2,192°	3,300°

Molecules of matter are held together by an attractive or cohesive force. As matter is heated, the vibration of the molecules becomes stronger. This vibration tends to overcome the attractive forces so that a solid first becomes liquid; then as the molecules pick up more energy, each one becomes so active that the substance becomes a gas. When fuel is in a gaseous state it can mix with oxygen and when ignited may unite with the oxygen to form a different compound.

FLOW OF GASES

Since in ordinary fires the main products of combustion are H_2O and CO_2 in a gaseous state, it is evident that these products will occupy more space than the original oxygen and the hydrogen and carbon which were in a liquid or solid state. Add to this the heat-expanded 79 percent nitrogen in the air which flows into the fire, and it is evident that the flow of gases away from a fire must be considerably greater than the flow of air into a fire.

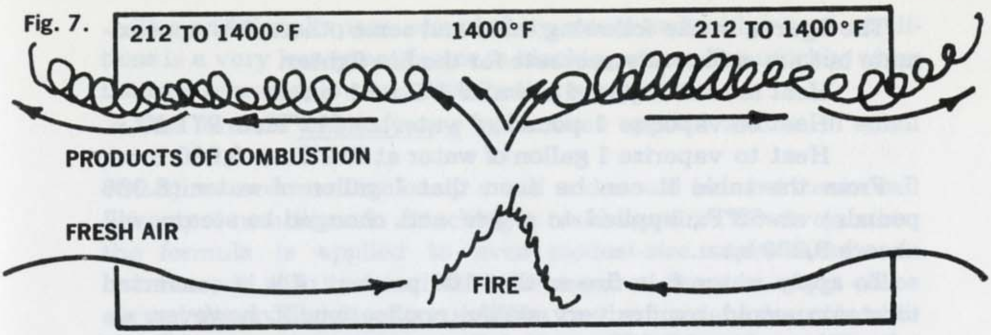
In a confined fire during the early stages before all of the walls and windows are heated above 212°F., the H_2O (water vapor) will condense and run down the walls and windows, allowing somewhat more space for the remaining products of combustion. After the walls of the structures are heated above 212°, the products of combustion must escape from the fire area if air is to flow in to continue the combustion process. When openings are available for both upper and lower ventilation, convection currents move products of combustion out and fresh air in to provide oxygen for combustion.

Fire fighters are well aware how rapidly these products of combustion traveling up stair wells or elevator shafts can heat areas above the fire. This is partly due to the actual temperature of the gases, but in the early stages of the heating of the upper area, most of the heat carried upward is carried by the water vapor. It requires 971 b.t.u. per pound to vaporize water at 212°F., compared to the 1 b.t.u. per pound per degree that is required to heat the water to 212°F., and also compared to the approximately ½ b.t.u. per pound per degree that is required to superheat water vapor above 212°F.

When this water vapor strikes materials that are below 212°F., it condenses and releases to these materials the 971 b.t.u. that were required in the vaporizing action. This method of transferring heat from one location to another is used in steam heating systems.

In confined fires this process carries heat to upper areas of a building quite rapidly. If there are no openings above the fire,

Fig. 7.



Condensation during the early stages of a confined fire will allow more space for products of combustion. Once walls and ceilings are heated above 212 degrees, condensation stops and products of combustion must be vented if fresh air is to flow in to continue the combustion process.

it acts to level off the temperature and creates and maintains a thermal balance. Most fire fighters have observed this condition of thermal balance many times on their arrival at fires. The fire fighter who understands the concept of thermal balance, and the temperatures necessary to maintain it, will be able to do his job easier and more efficiently. This will be discussed more thoroughly in succeeding sections.

UTILIZING HEAT

The preceding section dealt with some of the characteristics of heat and its production in fires. One of the main premises advanced in the preceding section was that in a 6-by-6-by-6-foot enclosure (200 cubic feet) there would be a relatively constant amount of heat, 7,400 b.t.u., present in the enclosure at any given moment during the early stages of a fire. It was also pointed out how the heat of vaporization of water, 971 b.t.u. per pound, works to carry the heat of combustion throughout the structure and to rapidly level off the temperatures in a given confined area.

Of major interest to both the officer and the nozzleman in fire situations is the amount of water needed to control a given fire. The officer is concerned with the total number of lines that must be laid and supplied with water, while the nozzleman is concerned with the size of line or rate of flow needed to control the fire in the area that has been assigned to him.

HEAT ABSORPTION

Now we are concerned with the rate of flow necessary for the nozzleman or nozzlemen in approaching a given confined area. To aid in determining the necessary rate of flow, we can review the amount of heat a gallon of water is capable of absorbing.

The figures in the following table and some others are approximate but are sufficiently accurate for the fire fighter.

Heat to raise 1 pound of water 1°F. = 1 b.t.u.

Heat to vaporize 1 pound of water at 212°F. = 971 b.t.u.

Heat to vaporize 1 gallon of water at 212°F. = 8,080 b.t.u.

From the table it can be seen that 1 gallon of water (8.336 pounds) at 62°F., applied to a fire and changed to steam, will absorb 9,330 b.t.u.

To apply water to a fire so that 100 percent of it is converted to steam would require very skillful application. If, however, we take 80 percent of 9,330, we find that 1 gallon of water will still absorb 7,460 b.t.u. when 20 percent of it is wasted. We assume this figure as reasonable efficiency.

Referring now to our 200-cubic-foot model room, we find that 1 gallon of water will absorb the heat present in 200 cubic feet of fire area at 80 percent efficiency.

From the preceding figures we can arrive at a suggested formula for the required amount of water in a given confined area:

$$\frac{\text{cubic feet involved}}{100} = \text{gpm flow}$$

ACTION OF STEAM

In addition to having the ability to absorb the heat produced in 200 cubic feet of space, 1 gallon of water converted to steam will occupy 200 cubic feet of space at 212°F. to inert the atmosphere in that space. When temperatures are above 212°, steam superheats and expands to occupy more space. At atmospheric pressure (14.7 psi) and 1000°F., the steam from 1 gallon of water will occupy 400 cubic feet.

Table 1 gives the approximate volume which steam from 1 gallon of water will occupy at different temperatures under normal atmospheric pressure:

Temperature Degrees F.	Volume Cubic feet per gallon (90 percent efficiency)
212	200
300	225
400	250
500	275
600	300
700	325
800	350
900	375
1000	400

The additional space occupied by steam under high heat conditions is a very important factor in blacking out a fire quickly when the rate of water flow and distribution are proper.

The formula $\frac{\text{cubic feet}}{100} = \text{gpm}$ when applied to fires in small structures seems ridiculously small and would in most cases call for only 1-inch lines in attacking a residence fire. However, when the formula is applied to even modest-size supermarkets or churches, it will be found that the required flows in many cases exceed the available water supplies or the fire department's ability to pump and distribute the water. This is evidenced by the continued loss of such structures when fully involved in fire.

REQUIRED WATER FLOW

For example, a 100-foot by 100-foot by 10-foot open area would require a flow of 1,000 gpm properly distributed to control a fire when the area was fully involved. The same area with a partition down the center could be controlled with a 500-gpm flow by making application first in one area, then in the other.

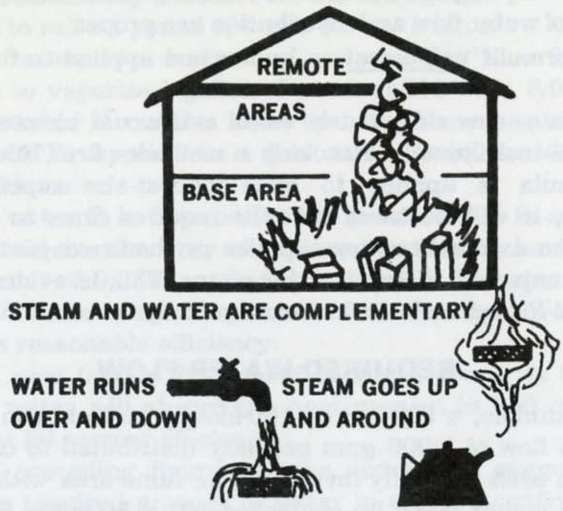
It should be stressed here that this is the flow required for the actual attack on the fire area to achieve control and in many cases does not constitute the entire water requirements for a given fire. Sound strategy will lead the officer to have additional lines to cover exposures and back up the lines actually working on the fire.

In a fire of any consequence stretching in additional lines to furnish master streams will be carried out while the attack is being made on the area of major involvement. Many factors, such as height, lack of openings, smoke, or unsafe structure, may prevent close approach to an involved area for proper distribution of water, and master streams will be needed to hold the situation.

If conditions are such that streams providing necessary rate of flow can be advanced to the involved area, skillful handling of the lines will control the fire, and make overhauling relatively easy. Inefficient handling of the required flow, or using flows greatly in excess of the required gallonage, can allow the fire to get out of hand, or at best make overhaul difficult.

Where large areas require several lines for the required flow, the coordination of these lines presents a problem. Unless they are very carefully coordinated, results will be less than ideal, because results are best when the ideal flow is introduced into an area, distributed throughout, and cut off when the fire blacks out, usually in about 30 seconds. This leaves the involved area full of steam to hold fires in remote areas in check, while overhaul is carried out. If flows are continued past the blackout point,

Fig. 8. Complementary action of steam and water.



steam in the area will be condensed, allowing air to flow in to feed flames that were shielded from the water in the initial attack. This may not be too critical if only one floor is involved, but if there are areas overhead such as false ceilings or other stories above the one where application has been made, fresh air instead of steam flowing into such areas can lead to the loss of the structure.

HEAT USEFUL FOR CONTROL

Firemen approaching a fully involved area, where a large amount of heat is accumulated and being produced, should regard the heat present as a most valuable weapon for controlling the fire. Skillful application of water can produce large volumes of steam to flow upward through a structure and control a fire in a remote area.

There are usually heated areas above a fire that cannot easily be reached with water streams. If a flow of steam can be continued into these areas, to suspend flame production, natural loss of heat will lower the temperatures in those areas. Even if some water can be applied in these remote areas, steam flowing into these areas can be helpful.

It is not possible in all cases to say which is more important—the cooling action of the water or the smothering action of the steam. The two effects are complementary—that is, either may accomplish extinguishment results impossible for the other. The smothering effect of steam is especially important in remote areas.

The wasting of heat by overapplication of water can make overhaul of a fire very difficult. The natural ventilation offered by ceiling temperatures between 212° and 300° cannot be replaced by forced ventilation. Smoke-laden air excessively cooled by overapplication of water often refuses to leave the structure under any amount of forced ventilation. In some cases it may be forced out of windows on an upper story and will cascade down the side of the building to again enter the building at a lower level.

While close coordination of all lines operating on a given situation is ideal, it is not easily accomplished on the fire ground. In an actual situation some lines may be stretched in and ready to go several minutes before enough lines are ready to furnish the required flows. To have these early lines stand by and wait would not be practical, yet if they make a partial attack and cool one end of the involved area prematurely, over-all results will be questionable.

However, if early lines are operated carefully, they can carry out an effective holding operation until a sufficient number of lines are in position for a killing attack. This holding operation is possible by having the early lines make a careful indirect attack as defined in the following explanation.

METHODS OF ATTACK

1. *Direct* method, applying the water directly to the materials involved in fire.

2. *Indirect* method, applying water to the heated atmosphere, striking as little as possible of the fuel or the walls of the structure involved.

3. *Combination* method, rolling the hose stream around the perimeter of the area, striking the walls of the structure and the fuel with the outside edge of the stream and letting the inner part of the spray stream cool the hot gases.

The direct method of attack is usually employed where heat accumulation has not yet become critical or the arrangement of the fuel is such that all that is involved in fire can be readily hit from the point of stream application.

The indirect method involves using spray streams to cool the heated overhead. The spray stream cools the hot gases, and steam is produced. This steam has some smothering effect in the base fire area, but it is of most benefit because of the smothering effect in remote areas where water cannot be readily or immediately applied by fire fighters.

If the volume of water is sufficient to cool the fire gases, this will be accomplished in 15 to 20 seconds. If the volume of the spray is excessive, this is not too critical as long as the stream does not hit the walls or ceiling of the structure. With the gases cooled, the spray will merely fall to the floor.

With the gases cooled, heat will radiate from the hot walls and ceiling or heat-production areas to the cooled gases in the vicinity of the spray stream, and steam production will take place at the perimeter of the stream to continue the flow of steam into the remote areas. In this manner it may be possible to push steam into the remote areas for 4 to 5 minutes.

When an indirect attack is being used as a holding operation, nozzlemen should be particularly careful not to strike the heated walls or fuel involved, until all lines are in position. Then all lines can be coordinated in making a combination attack, afterward shutting down and going in for overhaul if the structure is safe.

When a successful knockdown has been accomplished and sufficient heat left in the structure to provide natural ventilation, the building must be entered immediately and all overhaul lines operated carefully if the benefits of natural ventilation are to be preserved while overhaul is carried out. The maintenance of thermal balance in an area during overhaul and certain other types of attack will be discussed in the next section.

SPECIAL CIRCUMSTANCES AND OVERHAUL

The preceding section set forth a method of determining the required rate of nozzle flow for a given area and stressed the importance of careful use of the heat present for steam production and ventilation. It also defined the indirect and combination methods of attack and gave some of the factors which an officer or nozzleman should consider in choosing between them.

CLOCKWISE ROTATION

Early in this publication it was pointed out that the direction of rotation of the fire stream should be clockwise when viewed from the base of the nozzle. This rotation helps to push flame, smoke and steam away from the nozzleman when this is a problem. A counterclockwise rotation will not have the same effect and in many cases seems to draw flame, smoke and steam toward the nozzleman. This effect has been observed many times on the fire ground. It has not been the subject of sufficient research to specify the exact cause for the observed results, but it is surmised that the effect is created by electrical forces.

It is known that in flame production areas there are free electrons and positive and negative ions. Since there are many fire fighters who are not satisified merely to know that something happens, but want to know "why," this effect of clockwise rotation needs to be studied. In many cases, determining exactly what causes certain phenomena leads to fuller utilization of the natural laws involved.

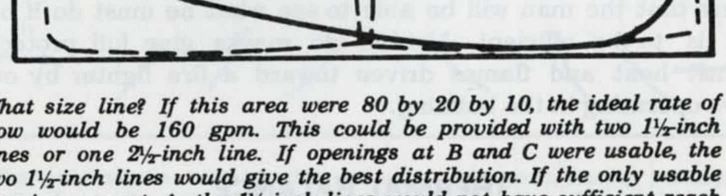
CHOOSING THE SIZE OF LINES

No mention has been made in the previous sections, of factors influencing the size of line to be used in distributing the required rate of flow. No hard and fast rules can be laid down for making this choice under varying conditions. The flow needs to be at least that required by the formula, but it does not need to be exact. For example, a required flow of 50 gpm could be supplied by a 100-gpm nozzle. The knockdown and point of shut-off will simply be quicker.

The illustration in fig. 9 suggests alternate methods. In another case, we may have a flow which can be supplied by either a 2½-inch line or two 1½-inch lines or other variations of lines.

In making this choice, several factors have to be considered, such as the available openings—doors, windows, etc.—the size and accessibility of these openings, the shape of the fire area in relation to these openings and the wind direction. The aim of the attack is to get the required flow distributed as evenly as possible over the entire area. It does little good to know that a 1½-inch line will control a given fire if the wind direction is wrong and the line cannot be advanced to the vantage point. It is just as futile to try to control a given fire requiring the flow that can be furnished by a 2½-inch line if the line has to be operated at a distance from a ladder. Where the vantage point is such that the 2½-inch line can be worked, it has about twice the capability of the 1½-inch, especially where the shape of the area is such that the extra reach of the 2½-inch line is needed.

Fig. 9.



What size line? If this area were 80 by 20 by 10, the ideal rate of flow would be 160 gpm. This could be provided with two 1½-inch lines or one 2½-inch line. If openings at B and C were usable, the two 1½-inch lines would give the best distribution. If the only usable opening was at A, the 1½-inch lines would not have sufficient reach and a 2½-inch line would be needed. Wind direction might make either one of these two choices the proper one on a given day.

Knowing the required rate of flow is helpful in many fire situations. However, this knowledge will be of little value if the department has not prepared to overcome the many difficulties it will encounter in distributing the water. Buildings with no windows or available openings, and fires above the second floor, present special problems in distribution of the required rate of flow. An officer who knows the flow required is still behind the eight ball if he does not have the manpower, equipment or water supplies in the area to meet that requirement.

OVERHAUL

There are many definitions for the word "overhaul" as used in the fire service. It is often hard to tell where the knockdown or control phase ends and overhaul begins. In many cases, the changeover from attack to overhaul is a matter of intuition on the part of the fire fighter rather than a point that can be exactly determined. For the purpose of this paper, overhaul will be considered as the fire fighting that takes place on the inside of the fire area after the main body of fire has been controlled. In some cases, overhaul may involve extinguishment of pockets of fire involving entire rooms within the structure.

In many cases considerable fire or water damage takes place after a fire has been controlled because of the inability of the department to quickly carry out the overhaul function. Fires have burned in false ceilings, through partitions, or up walls into new fuel areas and gotten completely out of control before the overhaul could be completed.

THE USE OF MASKS

In many cases, fires that get out ot hand during the overhaul phase could have been controlled if the department had been equipped with a sufficient number of selfcontained masks. However, the mere fact that a department is equipped with masks will not assure efficient overhaul. Masks provide a means for the fire fighter to breath in a smoke-filled building, but they do not assure that the man will be able to see what he must do if overhaul is to be efficient. Neither do masks give full protection against heat and flames driven toward a fire fighter by other crews operating in the building.

THERMAL BALANCE

The time to start planning for efficient overhaul is during prefire drill sessions, but unless careful thought is given to overhaul during the knockdown, conditions will be created which will make this function difficult, if not impossible.

Nozzlemen making the knockdown should strive for the ideal. If at the conclusion of the knockdown, the fire area is left with an even ceiling temperature of 300°F., conditions will be ideal for natural ventilation and easy and efficient overhaul.

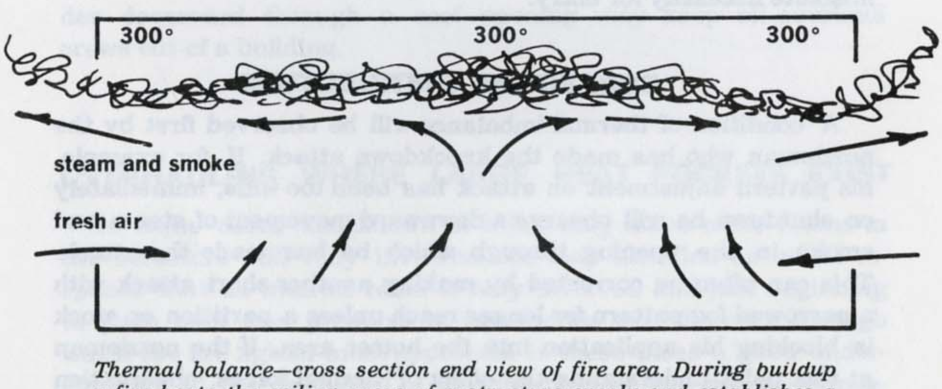
The lifting forces of the warm air (thermals) will be in balance throughout the area, and we can say that we have left the area with the same thermal balance that was developed as the fire built up but at a somewhat lower temperature. This will permit overhaul crews to move in rapidly as the fresh air enters the building at the lower levels and the remaining steam and smoke escape from upper levels.

THERMAL IMBALANCE

If, on the other hand, water distribution has been poor, we may have part of the area cooled to ambient temperature and other parts left with temperatures of 500°F. to 1000°F. The upward thermal forces in the hot areas will push steam and smoke out and downward in the cool areas and cause a circulation in the fire area which will limit visibility and hamper overhaul. The cool air will be heavily laden with carbon particles (smoke).

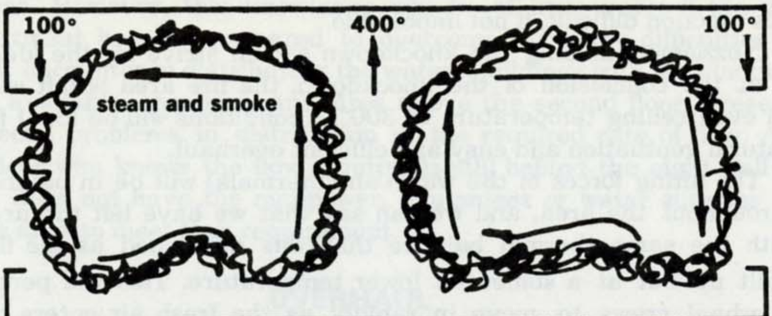
The greater the heat differential, the more violent this circulation will be. If cooling is continued on the perimeter, using a fog pattern too wide or a stream with insufficient reach, the problem is compounded and the heat in the hot spot will become more intense. This condition will keep the fire fighter from entering and

Fig. 10.



Thermal balance—cross section end view of fire area. During buildup a fire heats the ceiling areas of a structure evenly and establishes a thermal balance with smoke escaping from the top part of openings and fresh air entering at the lower levels. By careful distribution of water this balance can be maintained during knockdown.

Fig. 11.



Thermal imbalance. If water distribution is poor during knockdown, the thermal balance will be upset. Hot air goes up, cool air goes down, the greater the heat differential, the more violent the rolling action will be.

may allow the fire to burn through to upper levels and get out of control. In a single-story structure, burning through of the roof over the hot spot will relieve the situation.

When the area is quite large and several nozzle crews and more than one hot spot are involved, the interaction between the various thermal forces pose additional problems for the fire fighters.

TOTAL COOLING

If, on the other hand, rates of flow have been excessive or the right flow has been continued for too long a period, the entire fire area may be cooled to ambient temperature. In this case, as spot fires continue to give off smoke, we find a heavy, muggy, smoke-laden atmosphere which is very difficult to remove efficiently with any amount of forced ventilation. Overhaul will have to be carried out with limited visibility, and gas masks will be an absolute necessity for entry.

CORRECTING DISTRIBUTION

A condition of thermal imbalance will be observed first by the nozzleman who has made the knockdown attack. If, for example, his pattern adjustment on attack has been too wide, immediately on shutdown he will observe a downward movement of steam and smoke in the opening through which he has made the attack. This can often be corrected by making another short attack with a narrowed fog pattern for longer reach unless a partition or stock is blocking his application into the hotter area. If the nozzleman at this point understands the effect of thermal forces, observation of smoke and steam circulation will give him a good indication of where his hot spots are, even when they may be off to one side.

HOLDING THERMAL BALANCE DURING OVERHAUL FOLLOWING KNOCKDOWN

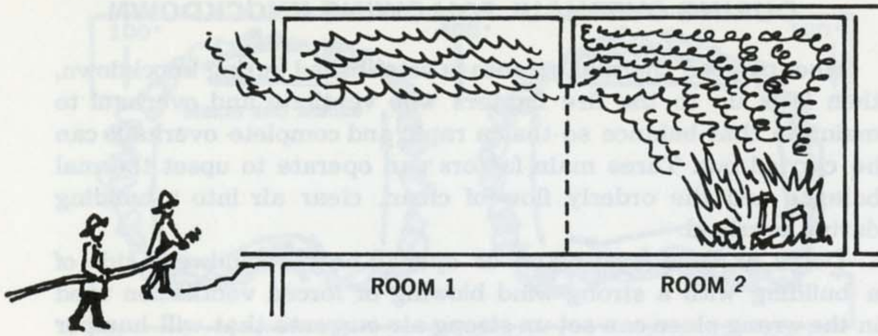
When a good thermal balance is established during knockdown, then it is up to the fire fighters who ventilate and overhaul to maintain that balance so that a rapid and complete overhaul can be carried out. Three main factors can operate to upset thermal balance and the orderly flow of clean, clear air into a building during overhaul.

1. Doors or windows broken or opened on the windward side of a building with a strong wind blowing or forced ventilation used in the wrong place can set up strong air currents that will hamper the orderly ventilation of the area being overhauled.
2. Spectators or firemen may block openings where streams of fresh air are flowing into the building.
3. Nozzlemen are the ones most often guilty of upsetting the thermal balance and hampering their own efforts or those of other overhaul crews operating in the building. Using a fog pattern during overhaul on the ground floor, for example, may upset the air supply and visibility for overhaul crews on the second and third floors. During overhaul all nozzles should be operated with relatively short bursts and on a quite narrow or straight-stream pattern.
4. If master streams have been used to protect exposures or clear the way for attack at certain openings, these streams must be shut down or very carefully used during overhaul so that they do not hamper or, in some cases, actually prevent the effective overhaul of the fire. A heavy master stream used over a fire can in some cases so cool the products of combustion that they drop to the ground to flow back into the building and cut off visibility for the overhaul crews. A heavy stream operated from an aerial ladder downward through a roof opening may keep all overhaul crews out of a building.

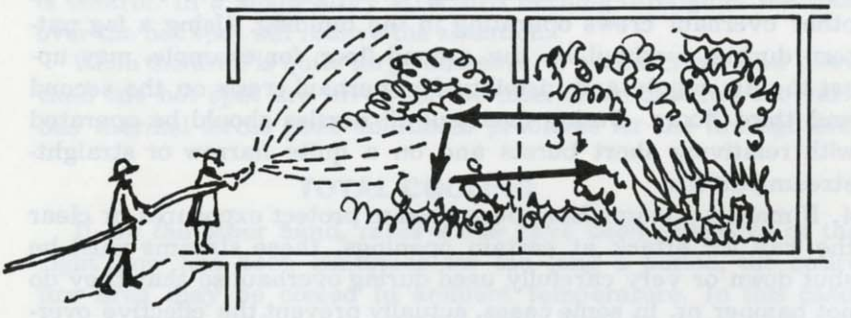
OVERHAULING WHERE LARGE HEAT POCKETS EXIST

In some cases knockdown of a fire may leave some rooms in the structure still fully involved. We may also find on initial response that an interior room is fully involved and just beginning to push heat and products of combustion into the area through which the fire fighter must approach. In these cases a good understanding of the principles of thermal balance can aid the nozzleman in extinguishing the fire quickly and with a minimum of physical punishment.

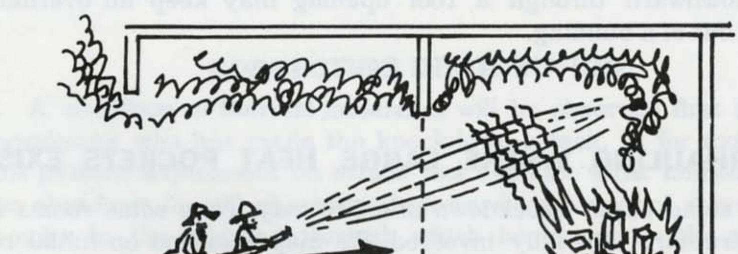
Fig. 12. Examples of attack.



To get to this fire for effective application of water, the fire fighter must approach through Room 1 where the products of combustion are traveling across the ceiling and spilling to the outside.



If a wide fog pattern is used in Room 1, the thermal balance will be upset and a wall of steam and smoke will drop in front of the fire fighter.



If the fire fighter approaches with a narrowed fog pattern directing his water into Room 2, he can get into position for effective use of his stream and at the same time maintain a flow of fresh air behind him for visibility.

The reaction of some nozzlemen in these cases is to use a relatively wide fog pattern on entering the structure. This action will cool the overhead and cause steam and products of combustion to drop to the floor, thus cutting visibility and approach to the actual fire. If, on the other hand, a nozzleman crawls along the floor, perhaps he can reach the doorway of the fire room where proper application to the main body of the fire can be made. In cases where both rooms are involved, the fire in the first room must be knocked down to the overhaul point before a crawling approach is made to the second room.

APPLICATION OF PRINCIPLES

If all buildings were alike and the conditions which influence fire behavior were always the same, the fire fighter might be able to do a creditable job without an understanding of the factors which influence fire behavior. Since this is not the case and fires in the same building will behave differently on different days, the fire fighter must have an understanding of the natural laws which influence fire behavior. The fire fighter who understands not only what but why something happened the way it did in a previous fire, is in a position to apply basic principles and his skill to the job at hand.

INSTRUCTIONAL AIDS ON WATER FOR FIRE FIGHTING

Iowa State University, through its Fire Service Extension program, has produced two educational films which are directly related to the subject of Water for Fire Fighting. These films incorporate much of the information contained in this bulletin. Titles of the films are "The Nozzleman" and "Coordinated Fire Attack."

The films are available for purchase from Fire Service Extension, Fire Service Extension Building, Iowa State University, Ames, Iowa 50010. The price is $150.00 per copy.

CORRECTION!
Formula on Page 14 should read:
$C_6H_{10}O_5 + 6\ (O_2) = 6\ (CO_2) + 5\ (H_2O) + \text{Heat}$