A Quantitative Approach to Selecting Nozzle Flow Rate and Stream, Part 1

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On a large scale, the American fire service has adopted a minimum initial attack handline flow of 150 gallons per minute (gpm) for an aggressive interior attack in residential structure fires.[1] National Fire Protection Association (NFPA) 1410, *Standard on Training for Initial Emergency Scene Operations*, 2010 edition, and 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*, 2010 edition, recommend that the first two handlines placed in service flow a combined total of 300 gpm once all first-alarm resources have arrived on scene. Several of the standard initial attack evolutions cited by NFPA 1410 provide that the first two lines flow 150 gpm each.[2-3] In one specific incident, this minimum flow rate recommendation was accepted by a department only after experiencing several significant firefighter injuries and a line-of-duty death.[4]

Revisiting the issue of initial attack handline flow rates is critical, given the increase in flashover and rapid fire progression incidents that are injuring and killing firefighters in residential structure fires. Since contents in the typical residential structure in the United States have trended away from organic and cellulose-based materials toward a greater percentage of hydrocarbons, the American fire service must seriously reconsider the manner in which the NFPA 1710 initial attack flow rate is met and applied, as well as consider an increase in the minimum acceptable target flow rate. Today's fire conditions leave little room for error.

The question we must ask is whether or not the first attack line used to make an offensive interior attack to protect firefighters and rescue trapped occupants, often without vertical ventilation or a backup line in place, is supplying a flow rate that is capable of rapidly knocking down a worst-case fire progression scenario and capable of instantly interrupting the fire's progression to flashover. This flow rate must immediately cool the high-temperature gases and smoke at the ceiling level while absorbing enough heat to effectively cool the surrounding walls, ceilings, floors, and other combustible contents that are about to flash over.

Several authors have examined and presented qualitative analyses of the various means by which firefighters mount an aggressive, yet safe, interior attack using 150 gpm. Many fire departments experience the successes associated with an aggressive interior attack using initial attack target flow rates of 150 to 185 gpm. We will use the interrelations of these authors' experiences and philosophies, engineering and thermodynamic research, and our recent nozzle flow-rate research to provide a quantitative methodology to answer the

following question:

> What is the safest, most effective, and most efficient single-handline flow rate and type for an initial residential structure interior attack?

FIRST-ALARM RESPONSE TIME STANDARDS

The American fire service prides itself on a rapid, aggressive interior attack. In light of this philosophy, the time-critical nature of applying the correct amount of water on the fire depends on understanding at what point in the development of a fire firefighters typically arrive and enter a burning structure. The efficiency and speed with which today's firefighters respond to occupied dwellings profoundly affect how precise the initial handline flow rate must be to deal with modern heat-release rates and the potential for flashover. National response time standards suggest that the initial arriving engine company typically making an offensive interior attack with just a single handline will often arrive at approximately the same time as many fires are approaching the flashover stage.

NFPA 1221

The first-time component that we must understand is the time from when a fire is first reported to the time when first-alarm resources initiate their response. According to NFPA 1221, *Standard for the Installation, Maintenance and Use of Emergency Services Communications Systems*, 2010 edition, an emergency communications center must answer the call for a report of a fire within 15 to 40 seconds from when it is received.[5] Correspondingly, the standard also recommends that fire call processing and dispatching be completed within 60 to 80 seconds after the call has been answered. (5) The worst-case scenario presents a situation in which 130 seconds (two minutes and 10 seconds) have passed from the time the reporting party attempted to notify the fire department of the fire to when the initial attack resources were notified.

NFPA 1710

This standard provides several first-alarm time and response standards for career fire departments. With respect to response times, once an alarm is received, the recommended turnout time is one minute and 20 seconds. (5) NFPA 1710 subsequently recommends that from the time the response begins until the first engine arrives at the scene should be four minutes maximum. (3) As a result, the first-arriving engine company that will begin the initial attack should expect to arrive within six minutes of the receipt of the alarm.

NFPA 1410

This standard provides several standards for first-alarm fireground operations, including minimum flows from handlines, supply lines, and master streams. Furthermore, NFPA 1410 provides time standards for various fireground operations initial attack resources can expect to put into operation. For purposes of this discussion, NFPA 1710 recommends that the sum of the two first handlines placed into operation at a structure fire be a minimum of 300 gpm and that the first handline flow be a minimum of 100 gpm. (3)

NFPA 1410 provides that the first two lines will be stretched, charged, and in operation with a water supply established within three minutes of the first engine company's arrival. (2) An initial arriving engine company will likely make an offensive interior attack without a backup line or water supply in place prior to entering the fire compartment if occupants are trapped. Considering this, two minutes is a reasonable time for the first

line to be placed into operation within the structure from time of arrival. A two-minute time allowance would be expected from time of arrival until water is applied into the main fire compartment. This accounts for the first-arriving officer's providing an arrival report, performing a thorough size-up, and providing proper direction to personnel prior to advancing the line into and through the burning structure to the seat of the fire.

As the preceding NFPA standards exist as recommendations that many fire departments strive to meet, they provide a reasonable estimate of the expected time frame within which an initial arriving engine company is likely to arrive at the scene of a reported structure fire. These standards, when considered together, provide that the first nozzle team will enter into the fire area in approximately eight minutes from the time the initial reporting call is made. What all firefighters must consider is that during the response to and suppression of a structure fire, there is truly no way to precisely determine how long the fire has been burning and the phase of development the fire is approaching.

2010 REPORT ON RESIDENTIAL FIREGROUND FIELD EXPERIMENTS

In April 2010, the National Institute of Standards and Technology (NIST) released Technical Note 1661, "Report on Residential Fireground Field Experiments."[6] In this research, live-fire studies were conducted using a burn prop built to the NFPA 1710 low-hazard residential structure parameters of 2,000 ft^2. One of the primary goals of this research was to study the effects that varying crew sizes have on reflex and operational times at structure fires and provide true operating times for typical fireground operations and tasks at a common residential structure fire.

The significance of the 2010 NIST report is that it provides true scale operational times using actual firefighters at a true structure fire and provides data that can be accurately applied to approximate at what time in the fire development curve firefighters most likely arrive on the scene, prepare to make entry, stretch lines to the fire compartment, and initiate fire attack. This report also used response time standards from NFPA 1221 and 1710.

In the study, times for firefighters to begin their travel to the fire started at 3½ minutes from when the fire started, and response times were three and five minutes. (6, 31) These times placed the first-due engine arriving at 6½ minutes and 8½ minutes from when the fire started.

The next timed parameter was "Advance Attack Line Time," which was the time from when the first engine arrived and stretched the first line and was in a position to initiate fire attack. (6, 38) The report states that a three-person engine company took 3 minutes and 36 seconds, and a four-person engine company took 3 minutes and 2 seconds to stretch the initial attack line to the fire. The time at which water was first applied to the room-and-contents fire area ("Time to Water") for the first-due engine company was 9 minutes and 15 seconds for the three-person company and 8 minutes and 41 seconds for the four-person company—a 34-second or 6-percent difference. (6, 39) Correspondingly, this recent research provides accurate evidence relative to the time the modern engine company arrives at the scene of a typical residential structure fire and begins fire attack operations.

FLASHOVER RESEARCH: TIME VS. TEMPERATURE

NFPA 921, Guide for Fire and Explosion Investigations, 2008 edition, defines flashover as follows:

> A transitional phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout

the space, resulting in full room involvement or total involvement of the compartment or enclosed area.

As a fire develops, heat and smoke from burning contents in a structure reach the ceiling, accumulate, and radiate extreme heat downward to combustibles at floor level, causing these materials to ignite.[7] Scientific research over the past 30 years reveals two facts: The growth of a compartmentalized structural fire often develops into flashover in less than 10 minutes from ignition, and the ceiling temperature associated with flashover is approximately 1,112°F.[8] As stated in NFPA 1710, flashover "hypothetically occurs in the room of origin" between eight to 10 minutes after ignition. (3) This estimate of eight to 10 minutes corresponds with research conducted by Spearpoint, Mowrer, and McGrattan, who compared flashover time models with actual fire measurements. Their research showed that flashover conditions developed in a furnished room 17 feet × 15 feet × 8 feet high within four minutes of igniting a loveseat and that flashover temperatures and signs were observed between nine and 10 minutes after initial ignition of the loveseat.[9]

We will discuss later how a ceiling temperature of 1,112°F plays a critical role in initial attack flow rate and stream selection choices. The heat-release rate (HRR) produced by superheated ceiling gases is discussed here to help us appreciate how quickly flashover can occur, even faster than within the previously indicated time frame of nine to 10 minutes. As presented by Kennedy and Kennedy, a radiant heat value of 20 kW/m^2 detected at floor level, associated with ceiling gas temperatures of 1,112°F, is a significant "trigger point" that can cause a fire compartment to flash over. (8)

Researchers examined the time required for flashover to occur with an upper gas temperature of 1,112°F (and) or a heat flux at floor level of 20 kW/m^2. In this study, many of the wall-covering materials tested flashed in less than 3 minutes and 20 seconds from the start of the test.[10] As will be examined later, once the preflashover ceiling gas temperature of 1,112°F is reached in a structural fire, a HRR greater than or equal to 1 megawatt (MW) is produced. (A watt is one joule of energy per second, and a megawatt is one million watts.) When materials in a room are subjected to radiant heat values greater than or equal to 20 kW/m^2, the combustible contents can flash over, leading to entire compartment involvement in less than two minutes. (10, 618) Furthermore, in the 2009 NIST report, "Firefighting Tactics for Wind-Driven Fires," a full-scale apartment fire displayed flashover conditions within five to six minutes of ignition.[11]

As mentioned above, the recently released NIST "Report on Residential Fireground Field Experiments" provides data on operational timeline, benchmarks, and reflex times and compares these times against the development of a residential structure fire. Although countless research projects provide that flashover can be expected to occur on average between eight and 10 minutes from ignition, one thing that must be considered is the variability of fire growth rates, which affects the time to which the peak HRR is reached. When a HRR of 1 MW is reached, a minimum radiant heat flux value at floor level of 20 kW/m^2 can be expected, which can rapidly lead to flashover and full involvement of the fire compartment, as well as rapid spread beyond the original compartment. (6, 46). However, not all fires burn at the same speed, or rate. The peak HRR and rate of growth of any particular fire is greatly affected by physical and chemical properties of the contents burning, including mass, surface area to volume ratios, and hydrocarbon content.

As an example, NIST states in this report that "a typical upholstered chair burning at its peak would produce a 1-MW fire, while a large sofa at its burning peak would produce roughly a 2-MW fire." (6, 46) With this in mind, the 2010 NIST residential fire study provided estimates of when the fire compartments, at slow, medium, and fast growth rates used in their research, would reach peak HRR values of 1 and 2 MW, both producing peak HRRs that could lead to flashover and total compartment involvement in the "absence of suppression." (6, 46) The times reported for these HRRs and respective growth rates are summarized below:

Fire Growth Rate	Time to Reach 1 MW	Time to Reach 2 MW
Slow	10 minutes	14 minutes, 8 seconds
Medium	5 minutes	7 minutes, 4 seconds
Fast	2 minutes, 30 seconds	3 minutes, 32 seconds

Firefighters understand there is no exact way of knowing during initial attack operations what the true target compartment and upper-ceiling temperatures are and for exactly how long the contents of a room have been exposed to radiant heat from ceiling gases that may be as high as 1,112ºF (minimum HRR of 1 MW). However, it is understood that initial arriving engine companies typically make access into burning buildings at approximately the same time that a burning room or an exposure room can flash over, as was demonstrated by bedroom fire tests NIST conducted in 1985. They demonstrated that flashover in bedroom fires can occur as early as four minutes after ignition with a HRR of 2 MW, depending on the surfaces used to line a room's walls and ceiling.[12]

As an example of the potential heat firefighters must deal with following a flashover, when wood paneling was used in the 1985 NIST test to line wall and ceiling surfaces, a post-flashover HRR of 7 MW was measured. (12, 19). This was an enclosed room test with conditions comparable to a compartmentalized structure. Post-flashover heat flux values (radiant heat at floor level) measured 130 to 220 kW/m^2, much higher than the aforementioned materials that experienced flashover when exposed to heat fluxes of 20 kW/m^2. (12, 12) What firefighters must learn from this research is that in enclosed structure fires, once preflashover ceiling gas temperatures and floor level radiant heating starts, floor and wall coverings and typical furnishings can flash over in less than five minutes from the time of ignition once the radiant heat at the floor level exceeds 20 kW/m^2. (12, 13) When firefighters are in the room next to the one that has just flashed over, preparing to make an attack, their position has now become a target of the radiant heat produced, which can instantly be much greater than 20 kW/m^2. Firefighters in such a position must be armed with the firepower to deal with such worst-case, ceiling-level peak HRRs and extreme radiant heat at floor level to prevent their location from flashing over next!

In March 2000, Andrew Fredericks discussed flashover research conducted by Vytemis Babruskas, Ph.D: "The most important factor in the speed with which a fire reaches flashover is the HRR .... If the HRR is high enough, flashover will occur."[13] Additionally, Fredericks referred to the *Fire Protection Handbook*, which states that the required HRR to initiate a flashover can be as little as 1 MW. A very important factor to note with respect to initial attack flow rates is that the *Fire Protection Handbook* further stated that a simple room-and-contents fire can rapidly produce temperatures and radiant heat that can cause a room to flash over. (13, 122)

The Center for Fire Research studies conducted in 1985 examined the burning rates in open and enclosed rooms with common furnishings and upholstery from that year. This report demonstrated the critical role that burning surfaces covering ceilings and upper walls play in the flashover sequence. In the open-room tests (no walls), heat output similar to that for flashover conditions of 1.2 MW occurred at approximately 660 to 720 seconds when the furnishings in the room were well involved. (12, 13) However, for the enclosed-room tests, flashover occurred in as little as 233 seconds with a HRR over 2 MW, which is the approximate time that the ceiling ignited. (12, 13)

To further investigate the effect walls have on flashover rates and temperatures, this research also analyzed the effect of wall-surface linings in tests using noncombustible gypsum and combustible plywood wall and ceiling coverings. For the room with gypsum-lined walls, the measured peak HRR was 2.5 MW; the measured peak HRR for the plywood-lined wall room fires was 7 MW. (12, 11) Simply by adding

combustible materials to the wall and ceiling surfaces, the HRR increased by 4.5 MW. This report further found that when the ceiling surface ignited, the burning rate of furnishings was significantly enhanced in all open-door room burn tests. (12, 19)

These full-scale fire tests measured the effects fire had on the standard furnishings in a typical United States Park Service (USPS) bedroom that was 8 feet wide, 12 feet deep, and 8 feet high with a floor area of 96 square feet. (12, 4) Room furnishings consisted of plywood furniture and a wood-frame bed with synthetic bedding materials. There were no televisions, radios, or other electronic devices. (12, 5) The fire load of this experimental room when lined with plywood walls was 3.03 pounds per square foot (lb/ft^2), almost two-thirds the fire load of the average recreational room in a metropolitan Washington, DC, single-family home in 1985, reported as 4.71 lb/ft^2. (12, 6)

With respect to the heat output of various materials commonly found in residential structures, wood, paper, cloth, and cotton produce 7,000 to 8,000 British thermal units per pound (Btu/lb). Plastic furnishings using polyurethane produce 12,000 Btu/lb, and those using polystyrene plastics produce 18,000 Btu/lb.[14] For each pound, plastics can yield approximately twice as many Btus than materials and items composed primarily of wood and other natural organic materials. As the fraction of hydrocarbon-based plastics in fire loads in modern construction materials and furniture increases, and since the amount of electronics in typical homes has increased since 1985, firefighters should anticipate the peak HRR in a room fire to be higher than the 7 MW recorded in the aforementioned bedroom fire study in which there were no electronics. Because of this, along with the increased use of energy-efficient building materials and windows engineered to contain heat, firefighters should expect a peak HRR greater than 7 MW, a greater amount of radiant heat at floor level, and an increased likelihood of flashovers occurring in less than eight to 10 minutes following ignition. (13, 120)

The 1985 NIST study's open-room tests (the fire area had no walls to contain heat and products of combustion) showed that the fire produced the minimum floor radiant heat level—20 kW/m^2—needed for flashover. However, in the closed-room tests, the measured floor heat flux was 130 to 220 kW/m^2 when the fires were not extinguished early. (12, 12) Firefighters making the initial interior attack will be operating in an enclosed environment that will have walls. Therefore, they must expect radiant heat levels equal to or greater than 20 kW/m^2 from adjacent fully involved compartments to affect unignited contents in the room in which they are operating or from which they are directing a stream.

This should sound an alarm for all firefighters: If a flashover of contents and materials at floor levels is initiated by a radiant heat level of 20 kW/m^2 in less than eight minutes, realize that flashover could very well occur in less than eight minutes in enclosed fire compartments with a possible floor heat flux of up to 130 to 220 kW/m^2 from upper surface and upper/gas smoke layers. Clearly, it is possible for a flashover to occur in less than five minutes from ignition.

With rooms in residential structure fires having potential peak heat outputs of 7 MW or more, when such preflashover conditions exist, there is little room for error, and the initial attack crew must select a stream that has the reach, thermal penetration, and droplet size to reach not only the burning fuel base but also the primary radiant heat sources that lead to flashover—the ceiling gases and smoke, the burning ceiling, and the burning wall materials simultaneously. This stream, at a minimum, must be capable of absorbing the maximum potential HRR at the ceiling. At the same time, it also must have enough heat-absorbing capacity and mass so that a significant portion of the stream will not turn to steam. These unevaporated droplets, if they are big enough, will then fall to the floor in droplet form, suppressing the primary fuel source and preventing unignited combustibles from flashing over.

HOW MUCH HEAT?

To estimate the adequacy of a flow rate for a single initial attack handline, we must first estimate the HRR of a given fire compartment or area. Once the worst-case peak HRR has been estimated, we can assess the ability of the selected stream to absorb the predicted amount of heat produced.

As referenced above, a HRR of 1 to 2 MW is commonly associated with the minimum upper-level gas temperature that can produce enough radiant heat to induce a flashover. Based on the square footage of the USPS/NIST test, the gypsum-lined rooms had a HRR per square foot of 0.023 HRR/ft^2, and the plywood-lined rooms a value of 0.07 MW/ft^2. The HRR/ft^2 value of 0.07 MW/ft^2 was recorded for the USPS test when plywood was used to line the ceiling and walls. Although the USPS tests produced a maximum HRR of 7 MW following flashover, the fire loading of an average home at that time was 1.55 times greater than the fire load of that room used in the test. With an increase in fire loading, a rough field estimate of the HRR could be expected to be up to or greater than 10.9 MW for a room of similar dimensions. Such an approximation is likely to be an oversimplification of the physics and thermodynamics behind fuel loading and the associated HRR. However, firefighters in the streets need a straightforward, user-friendly field value to help them roughly determine if their flow rates are in the "ballpark" of the flow rate needed to combat worst-case scenario HRRs that can rapidly lead to a flashover when no backup line is in place.

An office-type fire burning at 100 percent efficiency produces a HRR per square meter of 0.25MW/m2.[15] Converting this HRR per-area value to square footage yields a value of 0.023 MW/ft^2, which is the same value reported in the NIST/USPS test for the gypsum-lined walls. Although most homes use gypsum-lined walls, the walls may have combustible covers such as wainscoting, paints, wallpaper, pictures, paintings, and so on, so a value of 0.07 MW/ft^2, three times that of 0.023 MW/ft^2, provides a reasonable safety margin in estimating possible HRRs. This value also provides a margin of safety for those homes with high degrees of clutter, storage, and other fire hazards that so often are found in residential structures in which fires occur.

The NIST Building and Fire Research Laboratory (BFRL) published Technical Note 1618, "Fire Fighting Tactics Under Wind-Driven Conditions: Laboratory Experiments," in January 2009. In this research, a full-scale apartment was constructed in a fire test laboratory. It consisted of a bedroom, a living room, and a target room; all were connected by a common hallway that opened to a corridor (similar to a center-hallway apartment). The bedroom, selected as the fire's point of origin, measured 16 feet wide × 12 feet deep × 8 feet tall and was 192 ft^2. The fuel loading throughout the apartment consisted of carpeting, carpet padding, a television and lamps, and furniture such as chairs and mattresses; all were manufactured during 1998 and 1999. The walls and ceilings were latex-painted gypsum board. The calculated combustible fuel load in the bedroom was 4.02 lb/ft^2; in the living room, 2.5 lb/ft^2; and in the hallway, 0.98 lb/ft^2. (11) The fire was ignited in the bedroom in a trash can filled with paper positioned between an upholstered chair and a bed. (11, 64)

(1) A closeup of the larger droplets from a 15⁄16-inch smooth bore nozzle at 180 gpm. (Photos by Jason Vestal.)

The bedroom fires continued to grow until the bedroom glass window began to fail, producing an approximate HRR of 1 MW, which is equal to the value of 1 MW reported by the NFPA Fire Protection Handbook as the minimum HRR needed to initiate "flashover (in) a room with a normal sized opening." (13, 122). At this time, a researcher completely removed the window, and the fire was allowed to burn unchecked. Post-flashover observations of conditions made shortly thereafter revealed HRR values of 15 to 20 MW. A peak HRR for the bedroom-control test just after flashover conditions were observed was 14 MW. (11, 354)

As stated previously, a ceiling temperature of 1,112°F is required to produce enough radiant heat at floor level (heat flux) to cause contents, such as flooring and furnishings, to flash over. The square footage and the HRR of the bedroom in the wind-driven fire study provides a HRR/ft^2 of 0.073 MW/ft^2 with a fuel load of 4.0 lb/ft^2, only one pound greater per square foot than the 1985 NIST/USPS test, using modern-day furnishings. This most recent study excluded the fuel load contributions from the oriented strand board (OSB) subfloor and latex-painted gypsum walls and floors. These HRR values were obtained during the control portion of the NIST/DHS 2008 experiments (no wind applied to the structure while it was burning). The post-flashover peak HRR value of 14 MW in this most recent NIST test with gypsum-lined walls produced a HRR/ft^2 similar to the post-flashover HRR/ft^2 value from the 1985 NIST tests, in which the walls and ceiling were lined with plywood. This comparison suggests that in the 2008 test with noncombustible walls and a similar fuel load, a higher post-flashover peak HRR likely resulted from increased combustibility of the modern furniture in the 2008 tests.

In 2004, NIST released the "Cook County Administration Building Fire October 17, 2003: Heat Release Rate Experiments and FDS Simulations." The researchers examined the factors that led to this fatal fire. This study produced very precise heat-release rates for full-scale office fires, using building materials, office furniture, and electronics collected from areas of the Cook County (IL) Administration Building that were not destroyed in 2003. In previous office workstation fires, NIST discussed research that had produced a HRR/ft^2 value of 0.169 MW/ft^2, based on a combustible fuel load of 18 lb/ft^2.[16] The 2003-2004 NIST full-scale office tests recreated burning conditions at the Cook County Administration Building Fire and produced a HRR/ft^2

value of 0.103 MW/ft^2 using a fuel load of 17 lb/ft^2. (16)

Comparing the results from the 1985 NIST/USPS, the 2003-2004 NIST office fire studies with much higher fuel loads, and the 2009 NIST/DHS Firefighting Tactics Under Wind-Driven Conditions suggests that a value of 0.07 MW/ft^2 is an accurate figure to use to estimate the possible worst-case HRR at residential structure fires. The value of 0.07 MW/ft^2 for residential structures is consistent with real-scale fire test results over the past 20 years and correlates well against HRRs produced in office fires using similarly aged combustibles. However, with higher fuel loadings and more plastic electronic devices per square foot—i.e., a residential bedroom vs. an office workstation—these factors suggest that this value provides a margin of safety when attempting to establish a field value to estimate single-room peak HRR for contemporary furnishings and interior contents in residential structures based on the square footage of a fire compartment.

As noted above, flashover can be initiated with a peak HRR as low as 1 to 3 MW and a heat flux of 20 kW/m^2 radiating from ceiling gases to floor level. As will be discussed in greater detail below, firefighters in full structural personal protective equipment (PPE) can at best endure 500°F temperatures and a heat flux of 20 kW/m^2 for only 30 seconds. (11, 335) For a single stream operating from within a threatened compartment to be rapidly effective against a possible flashover, that stream must be capable of absorbing the heat produced from the worst-case scenario HRR for that particular compartment or an adjacent involved compartment within 30 seconds to provide the best chance for the survival of firefighters operating within or occupants that may be trapped in that space. When preflashover or rapid fire progression conditions are observed, firefighters committed to interior positions who cannot instantly exit the threatened area must be able to reduce flashover-inducing HRRs and heat flux with a single stream in less than 30 seconds.

With decreased sensory awareness, firefighters have a reduced ability to accurately and quickly determine environmental conditions and changes. In the most extreme cases of zero visibility, it is often difficult at best to observe flames in the overhead or other visual clues. Since flashover can occur at approximately the same time as the first hoseline is placed in operation in an offensive interior attack, firefighters may not have the thermal reference history to be able to recognize subtle temperature fluctuations and interior environmental transitions that can occur in a matter of seconds and initiate a flashover. This can cause firefighters to overcommit to an interior position so that if a flashover were to occur and their handline flow rate does not have the heat-absorbing capability to prevent or stop the fire's progression, they are likely in a fatal situation. Even with the most modern PPE, they likely would not have enough time to exit the structure without incurring serious thermal injury.

A given fire requires a specific amount of water to successfully absorb the heat produced in a relatively short time so that a developing flashover can be effectively stopped and occupants not wearing structural PPE can be instantly protected. With many modern residential structures having larger master bedrooms, family rooms, and kitchens, firefighters must expect a HRR greater than that associated with an 8- × 8-foot bedroom. The more floor space available, the more combustible materials inhabitants are likely to accumulate. As discussed above, firefighters can calculate field estimates of worst-case HRRs for residential, commercial, and office structure fires based on the square footage of the area compartment involved.

An average value of 0.07 MW/ft^2 is suggested for estimating the potential HRR from average residential bedroom fuel loads. For example, a fire that has flashed over in a room 10 feet × 10 feet, similar to that of a small bedroom fire, can be estimated to produce a peak HRR at flashover of 7 MW. However, for a larger room, such as a living room that measures 20 feet × 20 feet, a peak HRR of 28 MW can be estimated. Many modern residential structures contain master bedrooms, family rooms, or garages measuring at least 20 feet × 20 feet. When operating in an interior exposure position, firefighters who have advanced to an interior position close to the seat of the fire must be concerned with the peak HRR from adjacent rooms—open doors, hallways, and uncompartmented areas. Once flashed over, they can instantly expose adjacent exposure

compartments to flashover-inducing HRRs and radiant heat levels at the floor where firefighters are operating.

Table 1 lists various room dimensions and the estimated maximum HRRs for later comparison against the heat-absorbing capabilities of various flow rates and stream types.

Table 1. Estimated Maximum HRRs

Room Dimensions	Square Footage	Estimated Peak HRR (0.07 MW/ft²)
8′ x 8′	64 ft²	4.5 MW
10′ x 10′	100 ft²	7.0 MW
12′ x 12′	144 ft²	10.1 MW
15′ x 15′	225 ft²	15.8 MW
18′ x 18′	324 ft²	22.7 MW (160 gpm Solid Stream)
18.5′ x 18.5′	347 ft²	24.3 MW (162 gpm Solid Stream)
19′ x 19′	361 ft²	25.3 MW (180 gpm Solid Stream)
20′ x 20′	400 ft²	28.0 MW
21′ x 21′	441 ft²	30.9 MW
22′ x 22′	484 ft²	33.9 MW (150 gpm Fog Stream)
23′ x 23′	529 ft²	37.0 MW
25′ x 25′	625 ft²	43.8 MW
30′ x 30′	900 ft²	63.0 MW
32′ x 32′	1,000 ft²	70.0 MW

The heat capacity of water and its latent heat of vaporization define the maximum potential HRR that a given amount of water can absorb. The ceiling temperature needed to produce a flashover is 1,112°F. At an initial temperature of 64°F, the heat-absorbing capacity of water applied to a ceiling at 1,112°F is 4.65MJ/kg, which converts to 0.3 MW/gpm. (15-23, 25) This ceiling temperature is used as the worst-case scenario where firefighters would direct their stream at the ceiling should rollover or impending flashover conditions develop. As reported by Cliff Barnett, a New Zealand civil and fire protection engineer, a fog stream at 1,112°F has a heat-absorbing efficiency of 75 percent, and a smooth bore stream has a heat-absorbing efficiency of 50 percent. (15, 26)

Based on the heat-absorbing capacities of fog and solid streams, Barnett's Fire Flow Formulae (Table 2) are used to compare the heat-absorbing capacities for fog and solid streams when applied to the ceiling area with a temperature of 1,112°F just prior to a flashover.

Table 2. Fire Flows Based on Barnett's Fire Flow Formulae

Fog	Heat-Absorbing Capacity
95 gpm (Example target flow rate setting)	21.4 MW
98 gpm (95 gpm setting @ 75 psi)	22.0 MW
118 gpm (150 gpm setting @ 75 psi)	26.6 MW
125 gpm (Example target flow rate setting)	28.1 MW
131 gpm (150 gpm at 50-psi Fireground flow rate)	29.5 MW
132 gpm (150 gpm at 75 psi-no kinks)	29.7 MW
137 gpm (150 gpm single-gallonage fog @ 50 psi)	30.8 MW
150 gpm (150 gpm (50 psi nozzle) at 64 psi, no kinks)	33.8 MW
180 gpm (Example target flow rate setting)	40.5 MW
200 gpm (Example target flow rate setting)	45.0 MW

Solid Stream	Heat-Absorbing Capacity
127 gpm (⅞" tip @ 50 psi, average kinks)	19.0 MW
150 gpm (⅞" tip @ 50 psi, no kinks)	22.5 MW
160 gpm (⅞" tip @ 50 psi, rated)	24.0 MW
162 gpm (15/16" tip @ 50 psi, average kinks)	24.3 MW
180 gpm (15/16" tip @ 50 psi, measured with no kinks)	27.0 MW
185 gpm (15/16" tip @ 50 psi, rated)	27.1 MW
200 gpm (1" tip @ 50 psi, rated)	30.0 MW

When selecting a flow rate, firefighters must not only consider the specific stream's heat-absorbing ability but also understand the ability of the stream to reach, penetrate, and effectively cool ceiling-level smoke and fire gases at 1,112°F. If the walls, ceiling, and floors are not effectively cooled because of an ineffective stream, it is possible that these surfaces may retain enough heat to reignite, causing advancing firefighters to suffer radiant thermal burns and combustible fire gases to ignite when they fall back within their respective flammable range.

One gallon of water can absorb only so much heat per second. If the heat-absorbing capability, or knockdown power, of the flow rate is greater than the heat produced by the fire, the HRR, the fire will go out. William E. Clark refers to this required flow rate as the "critical" flow rate.[17] Conversely, if the HRR is greater than the heat-absorbing capability of the applied stream when it reaches the ceiling, the fire will not go out in a timely fashion to adequately protect interior operating nozzle teams and trapped occupants. In other words, the critical flow rate has not been delivered! For example, if a fog stream produces a flow of 150 gpm, then the HRR that the stream can absorb is 35 MW at 1,112°F. If a fire in a room is calculated to produce 20 MW, this flow rate will be effective in absorbing the heat produced. However, if the same stream cannot reach or penetrate the 1,112°F ceiling gases and smoke, or if the HRR is 40 MW, then the stream would not be able to effectively control the fire in the time desired for firefighter or occupant protection.

(2) A demonstration of the coverage the 15⁄16-inch stream affords.

Considering this, when you commit to an interior attack, you select an initial attack flow rate at the exterior of the structure. This gpm selection is based on exterior conditions from a distance, not on conditions inside the structure. If a handline with a flow rate of less than 150 gpm is taken into the structure, the stream's effective heat-absorbing capacity and flashover-inhibiting power may not be sufficient to rapidly combat the HRR if the entire contents of a room become involved.

The increasing use of lightweight building materials for initial construction as well as remodeling, repair, and renovation projects; improved insulating materials; and energy-efficient windows indicate that as use of these materials becomes more common, a greater percentage of fires will retain a greater amount of heat and combustible smoke in the fire compartment as compared with the past. As exemplified in tests conducted by Underwriters Laboratories, using ASTM Method E119, it has been demonstrated that modern lightweight building materials for residential and commercial structures, such as wooden I-beams and OSB for flooring materials, can fail in as little as six minutes on exposure to fire.[18] Increased use of lightweight building materials underscores the need to select fire streams that can do the following: (1) penetrate fire gases at the ceiling level and (2) immediately and effectively absorb the total heat output that is actively attacking exposed flooring and materials at the ceiling. Not all flow rates and stream types have the reach, momentum, or mass to penetrate fire and smoke gases rapidly approaching or at 1,112°F, and not all flow rates possess the heat-absorbing capacity, using a single stream, to effectively suppress a fire in an offensive interior attack in a relatively short time.

DEFENSIVE VS. OFFENSIVE FLOW RATES

Iowa Formula and Lloyd Layman

Keith Royer established the Iowa Formula by using Lloyd Layman's theory. "Chief Layman is credited with the introduction of fine water spray nozzles .... Layman did specify the criteria for water spray to be effective ... (including) no firefighters or occupants within the compartment. The last aspect is very important and clearly recognizes that the use of fine water sprays in combination with an aggressive interior attack is inappropriate and will result in injury to the firefighter." Royer's evolution of the flow rate formula was based on the volume (L × W × H divided by 100) of the largest single noncompartmentalized room, with no

interior life hazard, in which multiple 30° fog lines were used simultaneously to indirectly attack the fire for 30 seconds.[19] This form of attack assumed no offensive interior operations until after the fire was darkened down. Furthermore, this form of attack was based on the concept that all necessary handlines and the total volume needed were on scene prior to initiating the exterior attack. (19, 2)

National Fire Academy Flow

In the early 1980s, instructors at the National Fire Academy (NFA) "examined the practicality of the Iowa formula for normal operations," including use for an offensive interior attack initiated by a single engine company, concurrent search operations, vertical and horizontal ventilation, and sequential support operations. (19, 3) The instructors then surveyed a number of NFA students in simulated fire scenes, where the fire building was assumed to be 50 percent involved, the fire attack initiated with a single interior attack line, and "primary search and ventilation operations would be achieved simultaneously with fire flow operations." (19, 3) The students provided their own assessment of needed flows per line to operate such an interior attack. Based on their estimates, the instructors determined the corresponding average flow rate based on square footage vs. the estimated flow rate. The corresponding formula is (Area)/3.

Using the square footage NFPA 1710 provides for a two-story residential structure no more than 50 percent involved in fire, the NFA flow formula calls for a rate of 666 gpm. This could include total involvement of the entire second floor, totaling 1,000 ft^2 for multiple compartments. It is highly unlikely that any single compartment on the second floor of a typical residential structure would be 1,000 ft^2. As discussed above, a room measuring 23 feet × 23 feet, similar to that of a two-car garage or a large family/bonus room, covers a square footage of just over 500 ft^2. The corresponding single-line flow rate for such an area using this formula would be 167 gpm.

Using the HRR/ft^2 value of 0.07 MW/ft^2 discussed above, if a two-story residential structure of 2,000 ft^2 were 50 percent involved (1,000 ft^2), a total HRR of all simultaneously involved compartments would be estimated to be 70 MW. Based on the heat-absorbing capabilities of a single fog or smooth bore handline listed above at manageable nozzle reactions for a single person, more than one handline would be needed for this extent of involvement. However, for a room of 500 ft^2, an estimated peak HRR would be 35 MW, which would be much more likely to be controlled by the heat-absorbing capabilities from a stream with a flow rate in the range of 150 to 185 gpm.

NFPA 1710 FLOW RATE

NFPA 1710, Section 5.2.4.2.2 requires the "establishment of an effective water-flow application rate of 1,110 L/min (300 gpm) from two handlines, each of which shall have a minimum of 370 L/min (100 gpm)." (3, 9) In a personal communication with Chief (Ret.) Alan Brunacini, NFPA 1710 chair, the intent of selecting 300 gpm as the first-alarm interior attack flow rate was based on the ability to confine and extinguish an average single room-and-contents fire in a two-story residential structure fire of 2,000 square feet. This flow rate does not account for more than the involvement of one room.[20] Furthermore, this standard is based on a residential structure of low-hazard and with no basement and no exposures. (6,16) Firefighters must make the necessary adjustments and base their flow rates on the fires they are more likely to face and/or be injured on and face a higher rate of fire growth or flashover risk: high-hazard residential structures of multiple room involvement on arrival.

To meet the 300-gpm standard identified in NFPA 1710, the use of a 100-gpm handline is consistent with the NFPA 1710 standard of using handlines with a minimum flow rate of 100 gpm; however, the second handline

must flow 200 gpm. Assuming that a given fog nozzle could provide a flow rate of 200 gpm at the following nozzle pressures, the nozzle reactions for 50-, 75-, and 100-psi fog nozzles would be 71, 87, and 101 pounds, respectively. For 1½-inch hose, the friction loss at 200 gpm, using a traditional "C" value of 24, would be 96 psi per 100 feet.[21] A friction loss value of 62 pounds per 100 feet is calculated for a 1¾-inch handline using a "C" value of 15.5. (21) The pressures needed to flow 200 gpm through 1½-inch hose clearly indicate that 1¾-inch hose is a much safer and more efficient conduit for flow rates exceeding 125 gpm. Furthermore, 1½-inch hose at 200 gpm using fog nozzles would be limited to lengths of 300 feet to avoid dangerous discharge pressures, increased potential for burst lengths of hose, and very stiff hoselines that would be difficult to bend around the numerous corners and narrow hallways found in single-family and multiple-family dwellings.

FIREGROUND FLOW RATES

NFPA 1710 recommends that the first two attack lines operating at a residential structure fire, once all first-alarm resources are on scene, should flow a minimum of 300 gpm. Several of the NFPA 1410 standard residential structure fire attack evolutions provide that the first two operating handlines at a residential structure be two 150-gpm handlines is logical, given response and reflex times, potential for flashover, nozzle reaction, and simultaneous fire attack and primary search demands placed on the first-arriving engine company. When applied to the residential structure referenced in NFPA 1710, a minimum single handline flow rate of 150 gpm coincides with the NFA Fire Flow Formula, the NFPA 1710 300-gpm first-alarm flow rate, and the heat produced at a residential structure fire of low risk using a field estimate of a HRR/ft^2 value of 0.07 MW/ft^2.

Over the past several years, there has been a great deal of discussion on verifying the actual flows from various nozzles used for interior residential fire attack operations. Many of these discussions have highlighted the need for firefighters to test their nozzles to determine what their actual flows are.

Lt. Jay Comella of the Oakland (CA) Fire Department discussed how flow rates and operating pressures were examined after a fireground line-of-duty death. An initial attack handline flow rate of 150 to 185 gpm was suggested following a Board of Inquiry investigation identifying the causal factors that led to a City of Oakland firefighter fatality. (4) In another article, the authors suggested an initial attack flow rate of 180 gpm for a single handline based on modern heat-release rates and to provide a safe margin of error in case of kinks, elevation changes, and other typical fireground situations.[22]

KINK TESTS

In tests conducted at the Rockland County (NY) Fire Training Center, a series of common fireground kinks were imposed in the middle of a 150-foot stretch of 1¾-inch fire hose. Nozzles tested included a 15⁄16-inch smooth bore (180 gpm at 50 psi), a 150-gpm variable fog nozzle (50 psi), and an automatic 150-gpm fog nozzle (100 psi). The 15⁄16-inch smooth bore nozzle, at an initial flow rate of 180 gpm, maintained a higher average flow with kinks imposed (150 gpm) than the other two 150-gpm nozzles that started at 50 psi (133 gpm) and 100 psi (111 gpm). The double 180° kink flows were excluded from comparison for this report, since the authors' experience has been that this kink condition is most often encountered when a hosebed is not cleared prior to charging and is not that common and is not used for fire attack operations.[23]

In August and September 2008, members of Sacramento (CA) Metropolitan Fire Department's Command Training Center Hands-On Training Team flow-tested all of the department's handlines and nozzles, as well as a 15⁄16-inch smooth bore nozzle and a 50-psi, 150-gpm single-gallonage fog nozzle. The tests were to provide Metro Fire members with accurate flow data for all interior attack lines using department standard

fog and smooth bore nozzles. All nozzles were operated and flow-tested at the manufacturers' designed pressure of 50 psi (smooth bore) or 75 psi (fog). As reported in previous studies, actual flows from fog nozzles were found to be less than the stated flow. Conversely, from all smooth bore nozzles, flows either met or exceeded the flow rate for the specific tip diameter at 50 psi. Although 1½-, 1¾-, and 2½-inch handlines were tested, only the results of the tests for the 1¾-inch handlines are discussed in this article.

Another component of the Metro Fire tests included imposing the same kinks as was done in the Rockland County research. Wooden templates were constructed to ensure that the exact same angles were imposed on each repetitive test. In the Metro Fire tests, hose lengths of 200 feet were used, since most attack lines subjected to this extent of kinking in this department's experience exceed 150 feet. (Metro Fire uses a single 150-foot preconnected attack line; all other handline beds are dead/static loads of 400 feet or greater.) The first 50 feet and the last 50 feet of hose were kept kink free; kinks were imposed on the middle two hose sections. The results of the Metro Fire flow tests closely paralleled those of the Rockland County tests.

Table 3 provides the average flows with kinks imposed (excluding the double 180° kinks) from the Metro Fire tests. Note that all standard Metro Fire fog nozzles use an integral smooth bore tip should an engine company officer elect to use a smooth bore nozzle for fire attack operations. The standard Metro Fire fog nozzle used on 1¾-inch handlines is an adjustable-gallonage fog nozzle rated to flow 30 to 200 gpm at 75 psi, tested at the 150-gpm setting with an integral 7⁄8-inch tip rated to flow 160 gpm at 50 psi. The other nozzles tested were a 15⁄16-inch smooth bore nozzle and a single-gallonage fog nozzle rated to flow 150 gpm at 50 psi, with an integral 15⁄16-inch tip rated to flow 185 gpm at 50 psi.

Table 3. Fireground Flow Rate Chart

Fog Nozzle	Rated Flow	Tested Flow, No Kinks	"Fireground Flow"	Average Flow Reduction from Tested Flow
150 GPM Fog @ 75 psi	150	132	118	11%
150 GPM Fog @ 50 psi; 15/16" integral tip	150	137	131	4%

Smooth Bore Nozzle	Rated Flow	Tested Flow, No Kinks	"Fireground Flow"	Average Flow Reduction from Tested Flow
7/8" Integral Tip @ 50 psi	160	150	127	15%
15/16" Tip @ 50 psi	185	180	162	10%

One of the more significant findings was the ability of the solid streams, at similar initial flows and at lower nozzle pressures (50 psi), to maintain a higher average flow when kinks were imposed. Very similar results were produced in the Rockland tests. One interesting finding for fog nozzles is that as the design nozzle pressure increased from 50 to 75 to 100 psi for the 150-gpm fog nozzles, the average flow with kinks decreased from 135 gpm (50 psi fog) for Metro and 133 gpm for Rockland (50 psi fog) to 118 gpm for Metro (75 psi fog) and 111 gpm-Rockland (100 psi fog), respectively. This indicates that as the required nozzle pressure increases, the ability to maintain a flow near 150 gpm decreases when kinks are imposed on the hoseline—in other words, as the required operating pressure for a fog nozzle increases, it is more susceptible to flow reduction by kinks.

The flow that a nozzle team fights fire with must account for typical initial attack line problems such as kinks, car tires, unsecured doors, narrow hallways, and so on. This is even more true of engine companies operating with only three personnel, where two personnel are stretching and operating the handline with no additional assistance in the first few critical minutes of an initial attack. For purposes of identifying target flow, the authors call this average flow that takes into account reductions from standard kinks the "fireground

flow." Such kinks and flow-restricting conditions may not be identified and removed until other crews arrive well after the first line is operating within a structure (for instance a confirmed rescue/trapped occupant).

From Table 3, we see that the minimum initial target flow capable of providing an average minimum "fireground flow" of 150 gpm is 185 gpm. However, when the authors experimented with a measured nozzle inlet pressure of 75 psi with the 50 psi, 150-gpm fog nozzle, they measured a flow rate of 185 gpm. The calculated nozzle reaction was 81 pounds. Given that the goal of initial attack handlines is to select a nozzle reaction of less than 70 pounds so that the nozzle can be managed effectively and safely by one person, this nozzle pressure and flow will be excluded.

FLOW-RATE EFFICIENCY

Table 4 presents flow rates and calculated nozzle reactions the authors determined during recent flow tests. During initial attack operations, most engine companies in the United States are likely to select 1¾-inch handlines as the first two lines. (1)Since NFPA 1710 recommends a total flow of 300 gpm from the first two handlines, a handline with an initial minimum flow rate of 180 gpm, without kinks or flow restrictions, will be needed to ensure, with a good degree of certainty, that each nozzle is delivering on average 150 gpm over the course of the fire attack.

Table 4. Flow Rate Efficiency Chart

1¾-Inch Handline Nozzles, Listed in Order of Decreasing GPM per Pound Nozzle Reaction, (listed in order of decreasing efficiency)	Measured GPM (no kinks)	Nozzle Reaction	Flow per Pound of Nozzle Reaction (GPM/lbNR)	Nozzle Pressure	PDP	Tested Average Flow with Kinks (w/o 2, 180s)	Meets NFPA 1710, 300-GPM Requirement with 2 like lines? (yes/no)
150 GPM Single Gallonage Fog @ 50 psi NP	137 GPM	49 Pounds	2.8 GPM/lbNR	50 psi	97 psi	131 GPM	NO
15/16" Smooth Bore Tip, 185 GPM @ 50 psi	180 GPM	69 Pounds	2.61 GPM/lbNR	50 psi	140 psi	162 GPM	YES
7/8" Integral Smooth Bore Tip, 160 GPM @ 50 psi NP	150 GPM	60 Pounds	2.5 GPM/lbNR	50 psi	115 psi	127 GPM	NO
150 GPM Setting @ 75 psi NP (Adjustable Gallonage 30-95-150-200 GPM)	132 GPM	58 Pounds	2.27 GPM/lbNR	75 psi	125 psi	118 GPM	NO

Fog Stream
Solid Stream
DOES Meet NFPA 1710, 300-GPM Requirement with 2 like lines
DOES NOT Meet NFPA 1710, 300-GPM Requirement with 2 like lines

Considering that an initial minimum flow rate of 180 gpm is needed if two like lines are to be used to ensure a total fireground flow rate of at least 300 gpm, the nozzle reaction associated with this flow rate must be assessed to determine the safest and most efficient way for a two-person nozzle team to meet this standard for safety and effective fire attack operations.

In Table 4, the minimum nozzle reaction associated with a given nozzle capable of producing a flow (with kinks averaged in) from two similar lines meeting the 300-gpm NFPA 1710 recommendation is 69 pounds. In these tests, fireground flow rates produced by nozzles with nozzle reactions less than 69 pounds did not meet the NFPA 1710 recommendation. Conversely, although larger lines with flow rates approaching 300 gpm could be used, such as a 2½-inch handline, the associated nozzle reaction would exceed the recognized safe single-firefighter maximum nozzle reaction of 69 pounds. (13, 132).

A nozzle's flow rate efficiency can be determined by comparing the nozzle's flow rate against nozzle reaction. Table 4 reveals that when comparing flow rate against nozzle reaction, the minimum initial flow rate capable of meeting the NFPA 1710 recommendation from two like lines must have an efficiency greater than or equal to 2.61 gpm per pound of nozzle reaction. Of the nozzles evaluated, only two nozzles had reactions less than 69 pounds (single firefighter maximum) with fireground flow rates that meet the NFPA 1710 recommendation: the two 15/16-inch smooth-bore nozzles with nozzle inlet pressures of 50 psi. All

other streams evaluated in this test either had a nozzle reaction in excess of 69 pounds or a fireground flow rate, inclusive of kinks, of less than 150 gpm per line. This indicates that two like lines would not reliably meet or exceed the 300-gpm recommendation when typical hoseline management problems are encountered during early initial attack operations.

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