Fire Engineering

Close

A Quantitative Approach to Selecting Nozzle Flow Rate and Stream, Part 2

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Even the smallest flow rate nozzle, regardless of stream type, if operated long enough, can suppress any fire in a confined compartment. However, when the lives of trapped occupants or firefighters are at stake, an aggressive stream that can effect a rapid knockdown is needed to place an effective volume of water between the occupants and the advancing fire without steaming those people within the compartment or areas opposite the applied stream. As discussed above, the modern-day engine company should expect that its arrival time is in line with a flashover event. As provided by the National Institute of Standards and Technology (NIST) in the April 2010 report on Residential Fireground Field Experiments, a timed three-person engine company and a four-person engine company began applying water to the room-and-contents fires with an "early arrival," at 11 minutes and 24 seconds and 11 minutes and 11 seconds, respectively, with the fires producing a high release rate (HRR) of 1-2 megawatt (MW), which is within the HRR ranges necessary to induce a flashover.[1] These two factors alone necessitate that a single stream be capable of effectively and safely absorbing the heat release rate of the fire at hand while also capable of immediately reducing the chance of a flashover or stopping a flashover that may be well into development.

The "3D Fire Tactics" method, as presented by Grimwood provides an interior nozzle team with a method to buy additional time to retreat to a safety zone when impending flashover conditions are observed.[2] This technique suggests using high-pressure fog nozzles that produce droplets in the 0.2- to 0.4-millimeter (mm) range. This technique necessitates using "pulses" of fog spray less than one second in duration. This method and stream type are not intended to stop an impending flashover or to confine, control, or extinguish an interior fire. (2) Using this method to advance into a room necessitates that firefighters advance very close to the seat of the fire (as opposed to the safety provided by the reach of a straight or solid stream nozzle), which then necessitates that the nozzle operator adjust the fog back to a straight stream and use a direct attack to suppress the fire.

Grimwood notes the following:

- Water droplets in the 0.2- to 0.4-mm range evaporate at 1.5 meters (five feet) from the floor. (2)
- The water contained in the solid core of a straight-stream pattern offers a higher velocity stream with

less surface water that is able to evaporate at the lower levels of the room, which means that almost all the water from a straight stream reaches the ceiling and evaporates in the 1,112°F region as it breaks down into smaller particles on striking the ceiling. (2)
- Temperatures range between 572° and 752°F at five feet above the floor. (2)
- Only a solid stream can penetrate the fire gases in excess of 1,112°F. (2)

Grimwood points out that the 3-D fog tactic buys firefighters time to retreat in the context of an impending flashover. However, when a flashover is about to occur, because the nozzle flow rate cannot suppress the fire, the 3-D Fog Tactic may not instantly reach or cool ceiling gases at the flashover temperature of 1,112°F. Additionally, the fog stream would not rapidly affect ceiling gases and smoke at 1,112°F above the five-foot height and may not immediately affect an impending flashover or be able to stop radiant heat from ceiling gases that can ignite floor level combustibles. This is a concern, since the ceiling heights in most residential structures are eight to 10 feet.

The 3-D gas cooling should be considered as a preventive measure to momentarily pause a developing flashover condition as firefighters in danger are in the process of retreating to a safety zone. However, firefighters advancing into the structure may encounter such conditions as flaming in the overhead that is not readily apparent because of dark smoke at the ceiling. As stated by Grimwood, in this case, firefighters should consider retreating to a safer position and use the short-burst 3-D water-fog techniques “to grab some vital seconds before they vacate their position.” (2, 9)

Based on this statement, the 3-D method is a means for advancing into a fire area, not an in-place survival technique when a flashover is about to occur or is occurring. When situational awareness of fire conditions is limited or entirely masked, flaming in the overhead is often not easily apparent and the signs that signal an imminent flashover can be easily missed; firefighters in such a position will likely not have enough time to evacuate.

In an impending flashover, during an aggressive and committed interior attack, it will often take firefighters on the interior of a working structural fire more than a few seconds to exit the structure. According to Fire Department of New York (FDNY) Deputy Chief (Ret.) Vincent Dunn (a recognized subject matter expert on flashover incidents), time and motion tests published in the *Handbook of Fire Protection* have shown that the average person moves two to five feet per second when walking.[3] The question Dunn poses is, “How long can a firefighter take 1,000°F to 1,500°F temperatures on the neck, ears, wrists, and any other exposed portions of the body?” Dunn states that if there is a 1,000°F flame in a burning room that has just flashed over, and a firefighter, who is five feet inside the room, crawls back to the doorway at one-half foot per second, he will feel 1,000°F to 1,500°F temperatures on the portions of skin not covered by fire gear for two seconds. Firefighters who are 10 feet inside the room when the room flashes over and try to escape will experience 1,000°F to 1,500°F heat on the exposed portions of their bodies for four seconds. (3) According to Dunn, the point of no return for firefighters in a room that is flashing over is five feet. Beyond five feet, structural turnouts do not afford enough thermal protection during a flashover to provide a good chance of survival. (3)

RADIANT HEAT—HEAT FLUX

The 2009 NIST wind-driven report discusses firefighter survivability in flashover conditions in the context of heat flux, which is the intensity of radiant heat at floor level. Previous NIST research suggests that a firefighter in full structural personal protective equipment (PPE), when exposed to temperatures in excess of 500°F combined with a heat flux in excess of 20 kW/m2, will survive less than 30 seconds.[4] As ceiling gases produce a HRR of 1 MW just prior to flashover, the heat flux at the floor level will be at least 20 kW/m2. In this study, measurements in the fire compartments immediately following flashover showed “post-flashover heat flux conditions ranging from 60 to 160 kW/m2." (4) NIST researchers observed that all the fires analyzed produced conditions in the corridor (center hallway) downwind from the room of origin in excess of 500°F and 20 kW/m2. (4) Even in areas remote from the fire compartment, radiant heat at floor levels greater than 20 kW/m2 can be expected and rapidly provide the necessary radiant heat energy to cause a flashover in the adjacent room or compartment where advancing firefighters are likely positioned.

In the 2009 NIST study, heat flux-measuring instruments were placed in the bedroom, living room, hallway, and corridor, three feet above the floor, to measure conditions that would be observed at the same height as that of the head of a crawling firefighter. After the window was removed, temperatures in the bedroom, living room, and north end of the center hallway reached 1,112°F, and heat-flux values were at least 50 kW/m2 (the bedroom heat flux value was 70 kW/m2) within 120 seconds—well in excess of the survivable limit of 500°F and 20 kW/m2. (4, 336)

In light of the extreme heat produced just prior to and during a flashover that can instantly kill interior firefighters, Dunn provides three defensive procedures that can reduce the risk of flashover: (1) delay in venting the fire, (2) venting the fire, or (3) using a hose stream to cool the fire. According to Dunn, "Discharging a typical 1¾-hose stream into a smoke- and heat-filled room can completely stop a flashover."[5]

Further, Dunn says that using a 1¾-inch hose with a 180-gpm stream reduces firefighter burn injuries. FDNY began using 1½-inch hose in the 1950s for more maneuverability. The department switched to 1¾-inch hose with a 15⁄16-inch smooth-bore nozzle in the 1960s and obtained a 180-gpm flow rate. In the 1970s, FDNY adopted constant-stream fog nozzles. Because burn injuries were increasing and firefighters did not know how to use a fog nozzle, the FDNY administration ordered that the use of the fog nozzles be stopped. According to Dunn, the advantages of the solid stream are that less steam is blown back, it knocks down ceilings and breaks some old windows, and has a good reach. If you advance down a hallway with a 15⁄16-inch solid bore nozzle flowing 180 gpm, you can be sure you will not be blasted back by steam.[6]

It is logical that injuries will increase when using fog patterns in an interior attack, as the low-pressure region created at the fog nozzle tip is often held near the head of the nozzle operator.[7] As reported in 2004 by Knapp, Pillsworth, and Flatley, a fog stream flowing 150 to 180 gpm can also inject a volume of air well in excess of 2,000 cubic feet per minute (cfm) of air to the fire compartment and also creates air currents that can carry superheated air, steam, and smoke back to the nozzle.[8] In comparison, the 180-gpm stream from a 15⁄16-inch smooth bore tip was measured to move only 500 to 710 cfm.[9] These findings were the results of nozzle air flow tests that dramatically illustrated the effect that nozzle choices can have on air movement and firefighter and occupant safety during interior attack operations.

Dunn continues:

- A solid stream does not reduce temperatures as well as a fog stream. The 15⁄16-inch smooth-bore nozzle reduces steam burns, and we do not manage flashover with hose streams in the real world. This is done in flashover training only. In a typical apartment fire, if you direct a hose stream ahead, you will not be caught in flashover. Firefighters searching without a line are caught in flashovers. A 1¾-inch hose with a 15⁄16-inch nozzle is an optimum hoseline for maneuverability, nozzle reaction, and discharge for one firefighter assigned to the nozzle and a couple of backup firefighters. This 1¾-inch line is not used in commercial building fires, high-rise fires, or as a backup line, which necessitate 2½-inch lines. (6)

The NIST 2009 tests compared the performance of a fog stream vs. a solid stream in cooling and suppressing a fire compartment with a room of origin that was 12- × 16- × 8 feet with a square footage of 192 ft2. In the first 30 seconds, the fog stream actually increased temperatures from 400°F to 1,000°F, increased the HRR from 12 MW to 16 MW, and took 30 seconds to reduce radiant heat levels in hallways (heat flux at three feet above the floor). The temperature at the ceiling was still capable of producing enough radiant heat at floor level to cause flashover and significant injury to firefighters after 30 seconds. The study compared the heat reduction results when an 80-gpm 30° fog stream (applied from outside the fire building through a window) was used and also when a 160-gpm solid stream from a 15⁄16-inch smooth-bore nozzle was directed from outside of a window and directed at the ceiling into the room of origin with a temperature of 1,112°F. (4, 60-61)

When the fog stream was directed into the bedroom window, temperatures increased at the highest levels of the room and varied widely for the first 70 seconds. (4, 249) When heat flux values were measured for the living room and center hallway areas downwind from the bedroom, the values in both areas increased to 100 kW/m2. The center corridor heat flux took approximately 80 seconds to drop to 20 kW/m2, and the living room heat flux was still at 50 kW/m2 after 80 seconds. (4, 259) In the first 80 seconds after the stream was applied into the bedroom, the temperatures between the ceiling and one foot from the floor in the bedroom increased to above 800°F and to approximately 500°F in the hallway leading from the bedroom to the living room. The temperature decreased to no less than 392°F at three feet above floor level in the center hallway outside of the apartment entrance. (4, 253)

These observations are consistent with Layman's specific warning in 1952 that firefighters should not operate fog nozzles from interior positions inside a burning building, especially if there is a possibility of trapped civilians in the fire compartment. (8) As previously discussed, air flows from a 150- to 180-gpm fog stream have been measured to introduce in excess of 2,000 cfm to the fire compartment. Such a large infusion of air can accelerate the fire growth rate and associated HRR. (9)

Conversely, in the NIST 2009 wind-driven report, the 160-gpm smooth-bore stream, when swept across the ceiling of the bedroom, instantly dropped ceiling temperatures in all rooms below 1,112°F and to less than 500°F in approximately 30 to 50 seconds. The smooth-bore stream was also able to drop the HRR from 16 MW to 8 MW in the bedroom in the first 30 seconds—20 seconds faster than the fog stream. (4, 291) Again, as reported by Knapp, Pillsworth, and Flatley, a 15⁄16-inch solid stream at 180 gpm increased air flow by only 510 to 720 cfm into the fire compartment, which was much less than the fog stream at the same gpm, and caused "no movement of superheated gases or steam back toward the nozzle team, thus allowing the aggressive interior fire attack to continue." (9)

In the NIST 2009 wind-driven fire report, the heat flux at three feet above the floor in the room of origin began to drop instantly—from 90 kW/m2 to 20 kW/m2 in 1 minute, 40 seconds when the solid stream was used. Both the downwind living room and the center hallway heat flux values decreased to 20 kW/m2 in the first 45 seconds. In the first 70 seconds from the solid stream's being swept across the bedroom ceiling, the temperatures between the ceiling and one foot from the floor decreased to approximately 750°F. In the first 30 seconds, temperatures in the hallway leading from the bedroom to the living room dropped from 1,500°F to 200°F. In the living room, all levels instantly decreased from approximately 1,600°F to less than 1,112°F and to less than 500°F in the first 30 seconds. All levels in the center hallway outside the apartment dropped to less than 500°F in the first 30 seconds of applying the solid stream to the ceiling of the bedroom. (4, 291)

Not only should engine company members advancing a hoseline consider these results in making their flow rate selection, but firefighters conducting search operations opposite the nozzle and fire (such as vent-enter-search operations) or approaching the fire room in a hallway (such as approaching truck company members in a center hallway) should truly appreciate the significance of an engine company's members applying the correct flow rate in the correct form for their own safety.

Simply stated, at conditions indicative of an impending or active flashover, the 15⁄16-inch solid stream at 160 gpm was able to drop temperatures and heat-flux levels to conditions that structural PPE can handle within approximately 30 seconds. (4, 291)

KNOCKDOWN POTENTIAL: STREAM PENETRATION AND TEMPERATURE REDUCTION

The ability of a solid stream vs. a fog stream to reach and cool ceiling gases and effectively stop an impending flashover is directly related to the ability of the stream to penetrate ceiling gases and the size of the droplets produced by the stream. In 2000, Simon Davis at the University of Cambridge in New Zealand published "Fire Fighting Water: A Review of Fire Fighting Water Requirements: A New Zealand Perspective."[10] It reported the following:

- A smooth-bore nozzle will throw more water a greater distance than a fog nozzle because it converts potential energy to kinetic energy more efficiently. (10, 47)
- The solid jet will also penetrate a hot fire plume and be less affected by winds or other induced air-stream effects. (10, 27)
- The solid (stream) is thus more effective at reaching the fuel and cooling the surface, producing less steam to obscure the compartment and scald firefighters. (10, 47)
- Solid jets also entrain less air and thus cause less disturbance of the fire. (10, 47)
- The water requirement is more related to the specific heat content of the fuel and the thermal conductivity of the fuel surface than the energy released from the combustion process. For this reason, effective firefighting is best achieved by applying a solid stream of water that is swept over the fuel surface. (10, 93)

Fornell provides in his works that a solid stream is better able to penetrate high heat and thermal drafts, as the uninterrupted path of a solid stream keeps the water held in a tight mass. (8, 95) In comparison, Fornell notes that even a straight stream produced by a fog nozzle requires the water to be redirected several times in its path before exiting and thereby entrains a large amount of air between water droplets. Fornell states that at 30 feet, the solid stream covers two square feet and the fog stream covers approximately 100 square feet.

Contrasting the reach and penetration of a 185-gpm solid stream from a 15⁄16-inch smooth bore tip and that of a 185-gpm fog stream in a 30° narrow fog pattern, Fornell continues that at 30 feet from the nozzles, the solid stream delivers 92.5 gpm per square foot while the 30° fog stream at the same initial gpm provides only 1.9 gpm per square foot, assuming that the small droplets from the fog stream are able to penetrate the fire plume and thermal updrafts and reach the ceiling. (8, 95) Using these coverage values, it would take a 30° fog pattern at 1.9 gpm 48 minutes to provide the same coverage to surfaces and the seat of the fire as the 15⁄16-inch stream can in only one minute.

As discussed, the critical factor in stopping a flashover sequence is to simultaneously cool ceiling-level gases; elevated ceiling, wall, and floor surfaces; and also the seat of the fire producing the heat. Therefore, as the rate at which a volume of water can be directly delivered to such areas increases, so will the rate at which gas temperatures, surfaces, and heat sources are reduced. In near flashover conditions with a ceiling temperature of 1,112°F, a heat-absorbing capacity of 0.3 MW/gpm, and their respective efficiencies, the solid stream can absorb 13.9 MW/ft2, whereas the fog stream has a much lower heat-absorbing capacity of 0.43 MW/ft2. The differences in ceiling gas and surface cooling power, flashover potential reduction, and knockdown potential are clear.

EFFECT OF WATER DROPLET SIZE

In 1996, Stefan Sardqvist, Lund University Department of Fire Safety Engineering, reported droplet sizes for fog and smooth-bore nozzles.[11] He reported that fog nozzles produce water droplets with diameters smaller than 1.0 mm, whereas smooth-bore nozzles with tip diameters between 7⁄8-inch and 11⁄8-inch produce droplets as large as 2.0 mm in diameter. This concurs with the average droplet size of 0.25 to 0.35 mm for a fog nozzle as determined by testing conducted by the Fairfax County (VA) and Montgomery County (VA) Fire Departments and NIST in 1985. (8, 98)

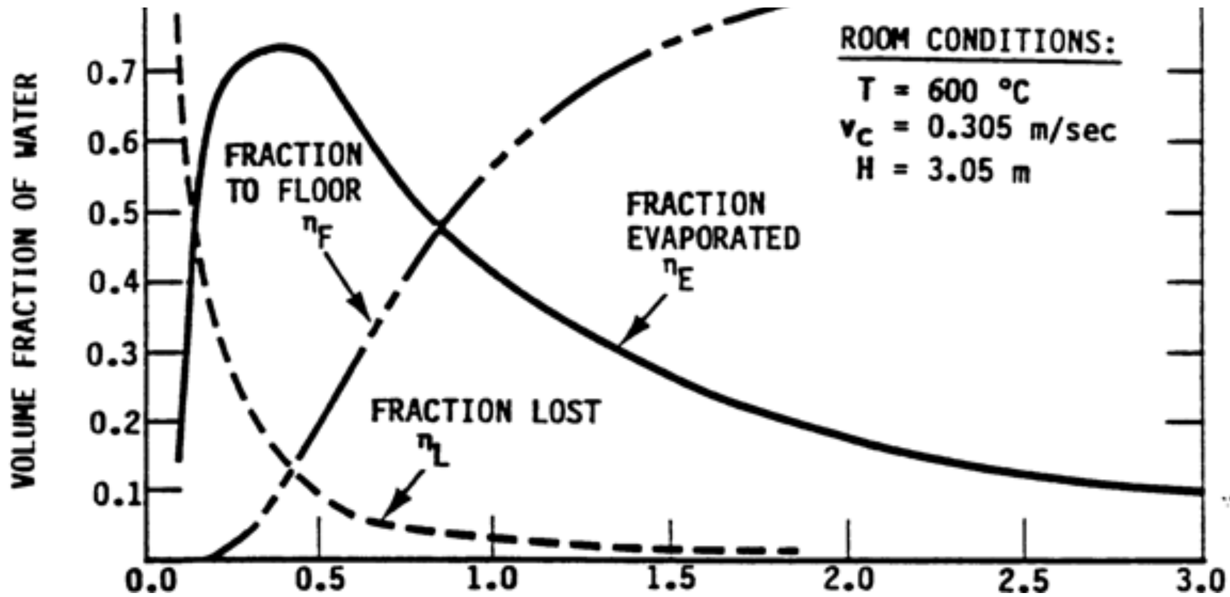
In 1992, the NIST report published by Pietrzak and Dale provided a graph of what happens to water droplets of a given diameter at a ceiling temperature of 1,112°F and a ceiling height of 10 feet. A droplet that does not evaporate at the ceiling will fall to the floor if it is too heavy for the thermal updrafts to lift. If it is too light, it will get trapped and circulate in the thermal updrafts. For droplets of the size reported by NIST in 1985 (0.35 mm from a fog nozzle), 75 percent of the droplets will evaporate at the ceiling, 12.5 percent will fall to the floor, and 12.5 percent will be caught in the thermal column.[12]

For the larger droplets produced from a smooth-bore nozzle (at least 1.0 mm), approximately 40 percent of the stream evaporates at the ceiling, 55 percent of the stream falls to the floor, and 5 percent is trapped in the thermal column. (12)

Water droplets that fall to the floor absorb heat radiated from the ceiling and can then assist with preventing ignition of the combustible materials that may lead to flashover. The more water that falls from the ceiling to the floor, the more that stream can prevent floor materials from igniting. According to Pietrzak and Dale, "A significant fraction of the drops with sizes less than 0.35 mm are blown away by hot gases and are not effective in achieving fire control … the larger drops become more effective, since they penetrate better, lose less of their volume by evaporation, and carry more water to the burning surfaces." (12)

Grimwood reports on research that assessed the ability of streams with different sizes of droplets to cool wall surfaces during the first two minutes of application: For a droplet 0.33 mm in diameter, the approximate diameter of a fog-stream droplet, reduced the wall temperature by 135°F; however, when droplets with a diameter of 0.78 mm were evaluated, the wall temperature was reduced by 383°F.[13] In other words, as the size of the droplets reaching heated surfaces such as ceilings and walls increases, the magnitude of the temperature reduction also increases. Therefore, to cool surfaces in a fire faster, the larger the droplets at the ceiling, the greater the temperature reduction throughout the entire compartment.At a droplet diameter of 0.8 mm (approaching the diameter of a solid stream droplet), 48 percent of the stream falls to the floor, 48 percent evaporates, and about 4 percent is lost in convection current, where it continues to recirculate in air currents produced by the fire. This 4 percent fraction of the stream does not evaporate, and it does not fall to the floor. It is essentially wasted, recirculating as hot steam in the center of the room. At a droplet diameter of 1.0 mm, approximately 42 percent is evaporated at the ceiling level, 55 percent falls to the floor, and 3 percent is wasted in the convection column.

Figure 1. Median Droplet Diameter



Source: NIST GCR-92-612, Pietrzak & Dale 1992, 62.

At 2.0 mm and larger diameters, 20 percent is evaporated at the ceiling level, 80 percent falls to the floor, and little to no water remains in the convection column. Given that the heat-absorbing efficiency of a solid stream when applied to ceiling gases at near-flashover temperatures has been reported as 50 percent, in this article, an average diameter of 1.0 mm will be used as the diameter for droplets from solid streams. This diameter size correlates well to the reported solid stream efficiency of 50 percent.[14]

As droplet diameter increases, the amount of water that can fall back to the floor and burning materials increases. Whatever isn't used to cool high-temperature fuel gases and hot surfaces at the ceiling level will fall to the ground, directly suppress the seat of the fire, and also prevent unignited fuels from reaching their flashover temperature. Larger droplets place more water where it is needed—the ceiling, walls, and floor—and trap less water in the convection column between the ceiling and the floor.

The fire sprinkler industry has studied water droplet behavior in fires extensively. Sprinklers must produce droplets that possess a mass and volume heavy enough to produce a terminal velocity that can fall from the ceiling down through the thermal column and land on the floor and smother burning fuels. Although the smaller and lighter droplets produced by fog streams have a higher surface area to volume ratio and are highly effective at reducing temperatures in the convection column, these droplets get trapped between the floor and the ceiling. In this location, these droplets do not cool burning ground fuels, burning walls, or ceiling surfaces and do not have an immediate effect on the 1,112°F flashover fuel gases in upper levels. Be aware that as more droplets and steam get trapped in the convection column in the center of the room, the more likely you are to experience steam burns to your upper body, neck, and ears.

Note: Referring to the stream-efficiency values reported by Barnett and Grimwood in 2005 (14, 26), the fog stream is 75 percent efficient in cooling a fire, and the smooth bore is 50 percent efficient. We reiterate that the wide fluctuation of temperatures when the fog stream was used vs. the instant reduction in ceiling temperatures when the solid stream was used in the 2009 NIST Firefighting Tactics report (4) supports Grimwood's earlier statement that a fog stream, when operated from the floor toward a ceiling with gases and smoke at a temperature of 1,112°F, is not as effective at reaching and cooling upper-level ceiling gases as a solid stream. (2, 4)

Water that falls to the floor of a fire compartment and covers unignited combustible materials, such as carpeting and furniture, can absorb 0.38 MJ/kg, or 0.024 MW/gpm, of radiant heat from the ceiling. (11, 53) HRRs produced by ceiling gases at a temperature of 1,112°F have been reported to be between 1.2 and 2.0 MW just prior to flashover. When selecting a single-line initial attack flow rate, choose a flow rate that can simultaneously cool the overhead and prevent floor-level combustibles from flashing over. A floor droplet rate of 84 gpm is needed to effectively absorb an overall HRR of 2 MW. Considering that solid streams produce droplets equal to or greater than 1.0 mm in diameter, with at least 55 percent of the stream flow falling back to the floor, we recommend a single-line minimum fireground flow rate of 152 gpm from a solid stream to penetrate the ceiling gases to ensure that 84 gpm will reach the floor in droplet form. Using a fog nozzle, which may have approximately 12.5 percent of its droplets fall back to the floor, you would have to apply a flow rate of 672 gpm to the ceiling to obtain a droplet fallout rate (DFR) of 84 gpm.

DROPLET FALLOUT RATES AND HEAT FLUX ABSORPTION

As discussed earlier, the handline selected needs to be able to effectively and rapidly absorb the peak HRR of a maximum residential room size (a master bedroom or a family room, for example) and at the same time absorb 60 to 70 kW/m2 of heat flux at floor level to interrupt the flashover sequence. The floor level heat flux values in all NIST tests were measured at 20 kW/m2 just prior to the development of flashover conditions and rapidly exceeded 60 kW/m2 once the flashover-triggering events occurred (when the window failed in the room of origin and the bedroom door leading to other rooms was opened). (4, 294)

Table 5. Fallout Rate and Heat-Absorbing Capability

Flowrate at Ceiling	Nozzle	Fallout Rate to Floor	Total Heat Absorbing Capacity at Floor (0.024 MW/GPM)	Heat Absorbing Capacity per m^2 (based on 343 ft^2 or 30.9 m^2)	Heat Absorbing Capacity (kW/m^2) vs 20 kW/m^2 minimum flashover inducing heat flux	Heat Absorbing Capacity (kW/m^2) vs 60-70 kW/m^2 early flashover progression heat flux
FOG STREAMS		12.50%				
95 GPM	Example Target Flow Rate Setting	12 GPM	0.3 MW	9.7 kW/m^2	Under	Under
118 GPM	150 GPM (75 psi) at 75 psi-Fireground Flow Rate	15 GPM	0.36 MW	11.7 kW/m^2	Under	Under
125 GPM	Example Target Flow Rate Setting	16 GPM	0.4 MW	12.9 kW/m^2	Under	Under
131 GPM	150 GPM (50 psi) at 50 psi-Fireground Flow Rate	17 GPM	0.4 MW	13.2 kW/m^2	Under	Under
132 GPM	150 GPM (75 psi) at 75 psi-no kinks	17 GPM	0.4 MW	13.2 kW/m^2		
137 GPM	150 GPM (50 psi) at 50 psi-no kinks	17 GPM	0.4 MW	13.3 kW/m^2		
150 GPM	150 GPM (50 psi) at 64 psi-no kinks	19 GPM	0.5 MW	16.2 kW/m^2	Under	Under
180 GPM*	Example Target Flow Rate Setting	23 GPM	0.55 MW	17.8 kW/m^2	Under	Under
200 GPM*	Example Target Flow Rate Setting	25 GPM	0.6 MW	19.4 kW/m^2	Under	Under
250 GPM*	Example Target Flow Rate Setting	31 GPM	0.75 MW	24.3 kW/m^2	Greater	Under
672 GPM*	Example Target Flow Rate Setting	84 GPM	2.0 MW	64.7 kW/m^2	Greater	Equal
SOLID STREAMS			55%			
120 GPM	3/4" Smooth Bore Tip at 50 psi, rated	66 GPM	1.6 MW	51.8 kW/m^2	Greater	Under
127 GPM	7/8" Smooth Bore Tip at 50 psi, Fireground Flow Rate	70 GPM	1.7 MW	55.0 kW/m^2	Greater	Under
150 GPM	7/8" Smooth Bore Tip at 50 psi, measured	83 GPM	2.0 MW	64.7 kW/m^2	Greater	Equal
160 GPM	15/16" Smooth Bore Tip at 35 psi, NIST FFTWDC Flow	88 GPM	2.1 MW	68.0 kW/m^2	Greater	Equal
162 GPM	15/16" Smooth Bore Tip at 50 psi, Fireground Flow Rate	89 GPM	2.1 MW	69.1 kW/m^2	Greater	Equal
180 GPM	15/16" Smooth Bore Tip at 50 psi, measured	99 GPM	2.4 MW	77.7 kW/m^2	Greater	Greater
200 GPM*	1" Smooth Bore Tip at 50 psi, rated	110 GPM	2.6 MW	84.1 kW/m^2	Greater	Greater

COLOR KEY

Fog Streams

Solid Streams

*Flow Rate (75 psi fog/50 psi solid stream) nozzle reaction exceeds 70 pounds; not a handline for a single firefighter to operate in an initial attack

Fallout rate at floor does not meet 20 kW/m^2 or 60-70 kW/m^2 heat flux levels at floor

Fallout rate at floor exceeds 20 kW/m^2 minimum flashover inducing heat flux, heat absorbing capacity is in range of 60-70 kW/m^2 early flashover heat flux levels at floor

Fallout rate at floor exceeds 20 kW/m^2 minimum flashover inducing heat flux, and exceeds 60-70 kW/m^2 early flashover heat flux levels at floor

"Flashover Stoplight"

<20 kW/m^2	Fallout Rate at floor does not meet/exceed MINIMUM flashover inducing heat flux at floor or early flashover progression heat flux at floor
60-70 kW/m^2	Fallout Rate at floor exceeds MINIMUM flashover inducing heat flux at floor and MEETS early flashover progression heat flux at floor level
> 70 kW/m^2	Fallout Rate at floor exceeds MINIMUM flashover inducing heat flux at floor and EXCEEDS early flashover progression heat flux at floor level

In the 2008 NIST study, the 15⁄16-inch smooth-bore nozzle produced a flow rate of 160 gpm. (4, 294) In tests conducted by the authors, the 15⁄16-inch smooth-bore nozzle produced a fireground flow rate (FFR) of 162 gpm. Using the 160-gpm flow rate, a field approximation of the maximum—in other words, worst-case—peak HRR that a 160-gpm solid stream can effectively absorb at a ceiling temperature of 1,112°F is 343 ft2

(30.9 m2) or a room 18.5 feet × 18.5 feet, which is estimated to produce a peak HRR of 24 MW.

When 160 gpm is applied at the ceiling, a DFR of 55 percent and approximately 88 gpm is predicted to fall to the floor onto burning materials and unburned fuels. Once on the floor, this water that is collecting on unburned fuels can absorb 0.38 MJ/kg, or 0.024 MW/gpm, of radiant heat. At 0.024 MW/gpm, a DFR of 88 gpm can absorb 2.1 MW at floor level. Dividing 2.1 MW by the maximum square footage associated with the peak HRR that the 15⁄16-inch solid stream can handle (fireground flow rate of 162 gpm) predicts that 89 gpm at floor level can effectively absorb a heat flux value of 69.1 kW/m2. This potential heat flux capability value for a 160-gpm solid stream is similar to, and slightly exceeds, the preflashover heat-flux values reported by the 2009 NIST study. By rapidly sweeping the stream across the ceiling when preflashover conditions are observed, a nozzle team should be able to distribute droplets throughout an 18-foot × 18-foot room successfully.

If a solid stream with a heat flux capability of exactly 20 kW/m2 for an 18-foot × 18-foot room is desired, an initial fireground flow rate of 46 gpm would be needed, and a DFR of 25 gpm would be predicted to fall from the ceiling. Although this droplet rate could, in theory, absorb the minimum floor heat flux value of 20 kW/m2 that can initiate a flashover, the flow rate of 46 gpm from a smooth-bore nozzle at the ceiling could address only a HRR of 6.9 MW at the ceiling level. Solving for area, at a HRR/ft2 of 0.07 MW/ft2, the maximum square footage this 46 gpm stream could handle would be 100 ft2, or approximately a room 10 feet × 10 feet. A flow rate of 25 gpm at the floor does not leave much room for error, and the flow rate at the ceiling does not provide enough flexibility to address many rooms in a residential structure that are often larger than 10 feet × 10 feet and that are encountered in a progressive multiroom interior attack.

Although it is not possible to flow 672 gpm from a fog nozzle in an interior attack with a single nozzle team, you can easily flow 152 gpm from a single smooth-bore handline. As noted above, the 15⁄16-inch smooth-bore nozzle delivers 180 gpm without kinks and an FFR of 162 gpm when flows with kinks are averaged. With kinks averaged, the flow of 162 gpm from the 15⁄16-inch smooth-bore nozzle has the reach, penetration, and heat-absorbing capability to absorb the heat produced in a typical residential room near flashover up to 347 ft2, or a room that is 18½ feet × 18½ feet and, with no kinks, a room that measures 19 feet × 19 feet. These values indicate that the 15⁄16-inch solid stream, with or without kinks, can rapidly knock down a fire in a room of dimensions in the range of up to 18 to 19 feet on each side. The average flow rate of 162 gpm with kinks produces a DFR of 89 gpm with a heat-absorbing capability at floor level of 2.14 MW. When no kinks are imposed on the 15⁄16-inch handline, a floor droplet rate of 101 gpm with a predicted maximum heat-absorbing capability on floor surfaces of 2.38 MW is possible. This suggests that the solid stream produced by the 15⁄16-inch smooth-bore nozzle also can absorb a considerable amount of radiant heat at floor level where unignited combustibles are located, thereby providing a secondary protective factor to minimize the chances of a flashover.

The effectiveness of the 15⁄16-inch stream and its associated characteristics were demonstrated in the NIST wind-driven study. The 15⁄16-inch smooth-bore nozzle produced a flow of 160 gpm at 35 psi and exhibited dramatic and instant results in reducing heat release rates, ceiling temperatures, and radiant heat at floor level in approximately 30 seconds in several of the fire apartment rooms, hallways, and the center corridor outside of the apartment. This suggests that the heat-absorbing capabilities of a 160-gpm solid stream can handle the post-flashover conditions associated with a fully involved room at a HRR of 0.07 MW/ft2 in an effective amount of time, even when nozzle pressure is less than 50 psi because of various fireground situations that can reduce nozzle pressure commonly encountered on the fireground. The rapid knockdown observed with a solid stream at a flow rate of 160 gpm suppressed a fire at the HRR measured demonstrated under closely monitored conditions that this flow rate and stream type rapidly improve conditions for firefighters who may be approaching or operating in such a hostile and rapidly changing environment.

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We have presented a quantitative methodology for selecting an initial attack flow rate and stream type for use in an interior attack using a single handline. The initial line must be of a flow rate and type that can penetrate the elevated temperatures and smoke at the ceiling level, instantly and effectively absorbing the anticipated heat release rates from interior compartment fires approaching flashover.

In addition, today's understaffed engine companies must be able to safely and efficiently handle the nozzle with one nozzle operator. The flow rate must enable the interior attack nozzle team to protect itself and trapped occupants by rapidly cooling all levels in a compartment, should the signs of an impending flashover develop. Last, the initial flow rate and stream type must produce, on average, a flow rate that, even when reduced by kinks and elevation changes, will reliably be able to instantly and singlehandedly defeat preflashover conditions with a single stream. This approach to identifying a target flow rate and selecting a stream type provides a nozzle team with the firepower to rapidly reach, protect, and rescue trapped occupants; minimizes the nozzle team's likelihood of being subjected to a flashover; and provides for a reliable, aggressive, and rapid knockdown to freeze the fire's progression to a possible flashover.

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