ENGINEERING CRITERIA FOR WATER MIST FIRE SUPPRESSION SYSTEMS

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ABSTRACT

This paper discusses a number of practical issues relating to the design of water mist fire suppression systems. There is presently a lot of interest among fire safety engineers in using water mist systems as an alternative to halon, on the basis that the mist will act like a gaseous suppression agent to fill all recesses of a compartment. Although there is a growing confidence that water mist systems can successfully extinguish flammable liquid pool fires and high pressure jet fires with small amounts of water, engineering criteria are needed to allow designers to match a water mist system to a range of fire scenarios and compartment types. This paper draws a parallel between the long-established practices for design of standard sprinkler systems, which allow any experienced designer to custom-fit a sprinkler system to a wide variety of fuels and buildings, and the need for similar design principles for the design of water mist systems. Research being carried out by various research agencies has just begun to document the information required to establish general design criteria for mist systems.

Starting with the need to define both the fire hazard and the fire safety objective, this paper presents information on characterizing sprays suitable for water mist systems. It points out that macro-scale effects in large volume compartments cause agglomeration of droplets, so that what starts out as a very fine spray ends up as a much coarser spray. It also points out that the types of nozzles available for producing suitable fine sprays have, at best, fairly high pressure demands and in the case of air-atomizing nozzles, very high compressed-air demands. These factors set a practical limit on the size of compartment that can be protected in a cost-effective way by total flooding systems. An alternative to total-flooding systems for larger compartments would be zoned piping linked to a sophisticated detection system. Much experimental work will be needed to validate such systems.

The matter of determining the spray flux density required for suppression is discussed in depth. Spray flux density is likely to vary by several hundred percent throughout a compartment as a result of removal of spray on the surfaces of obstructions. It is more efficient to achieve high localized densities in the vicinity of the known fire source by strategic location of nozzles, than to attempt to create a single uniform density in the compartment. More than spray density is required to extinguish flames, however. The

spray must have enough kinetic energy to interact turbulently with the flame. In this respect, water mist does not act in the same manner as gaseous suppressants. Finally, the paper discusses some of the factors relating to ventilation of the compartment, and the effects of spray systems on the pressure conditions in the fire room. The feasibility of discharging a number of air-atomizing nozzles into a completely closed compartment is questioned. The effects of sudden contraction or expansion of hot gases or steam upon application of the water spray are also discussed.

This paper does not state conclusive design criteria for particular hazards. Instead, it concentrates on the general principles of defining the hazard, deciding on the objective or desired performance of the system, understanding the practical limitations of the equipment, and preparing for the actual interaction of the system with the fire. It is from this basis that the development of design criteria and procedures for a wide variety of hazards must start. Design criteria for particular hazards will have to be built, case by case, application by application, as they were for standard sprinkler systems. With the strong demand to build a data base for efficient design quickly, however, there is a need to combine the efforts of all agencies working on the problem.

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Introduction

This paper will highlight some of the engineering issues that need to be addressed in designing a fire suppression system based on very fine water sprays, i.e., water mist. Considerable international interest has been generated in developing such engineering criteria for the following reasons. The first is an economic interest in reducing the volumetric water requirements for suppression systems - it is understandable that the promise of a fast-acting, low-water-volume fire suppression system should attract considerable attention. A second reason is that many fire safety specialists view the use of a fine mist as a potential replacement for gaseous fire suppressants, assuming that the mist will be drawn by convective air movements into all recesses of the space – therefore, intense international interest in finding an environmentally benign alternative for halon is motivating research into these systems.

Over the last few years, there have been a number of impressive demonstrations of the effectiveness of very fine water mists in extinguishing gas jet fires, flammable liquid spill fires, and even fires involving plastic foam furnishings. Evans and Pfenning (1985) demonstrated how a fine mist injected into a high velocity methane gas jet below the flame front could extinguish a 200 MW flame within seconds. British Petroleum Ventures (BPV) in the UK, among others, has demonstrated similar rapid extinguishment of gas flares on off-shore oil drilling platforms, by injecting water mist directly into the gas stream at the base of the flare. Tests done at the Swedish National Testing and Research Institute at Borås, and at SINTEF, the Norwegian Fire Laboratory, have demonstrated how effective water mist systems can be for diesel fuel and crude oil pool fires in enclosures (Olsson & Ryderman 1990; Wighus 1991). In the petroleum industry, water mist systems have been demonstrated by BPV to extinguish up to 25 MW fires involving spilled fuel and a pressurized hydraulic jet flame. In the aviation sector, much work has been done in the last 7 years in the UK and in the USA to develop water mist fire suppression systems for use on aircraft, to protect the occupants from an external pool fire long enough to provide time to escape. The aviation industry's need for a very low weight system has driven the technology towards making maximum use of a small volume of water to block radiant heat and provide cooling in a relatively large volume space (Hill 1992). There are other examples of where water mist fire suppression systems are already being used to protect special risks, such as on submarines (Soja 1990; Yard 1988).

So with what appears to be an extensive level of experience, internationally, in the use of fine mists for fire suppression or control, it is interesting to note that there are many fundamental questions still being asked about how to actually design a water mist system for a particular fire hazard. The Canadian, British and American Navies, for example, are aware of the potential benefits of use of water mist for protecting shipboard spaces that are presently protected by gaseous fire suppression agents, such as halon. However, before proceeding to replace all existing halon suppression systems with water mist systems, they would like to have answers to some basic engineering questions, such as:

- What are the characteristics of a "fine spray" that are critical to its effectiveness?
- What technologies exist for producing fine sprays with the desired characteristics, and which are the most reliable and cost effective?
- How does one relate the spray characteristics of drop size and rate of application to the type of fire possible in the space, and the geometry of the space?
- What degree of control should be expected – complete extinguishment? ... or can reduction of heat release rate and room temperature be considered to provide the desired performance? If so, how much reduction?

This list is not exhaustive, but it serves to illustrate the fact that certain engineering principles are required before water mist fire suppression systems can be designed with confidence for critically important facilities. There are numerous compartment conditions which will affect the performance of a fire suppression system, including floor area and ceiling height, obstructions, fuel type and configuration, and ventilation.

It is interesting to compare the engineering information that exists today for the design of automatic sprinkler systems, with that which does not yet exist, but is needed, to standardize the design of water mist fire suppression systems. The designer of a sprinkler system follows well-established practices to match the sprinkler system to the type of fuel and its potential heat release rate, and take into account ceiling types and heights, sprinkler spacing, sprinkler response time, activation temperatures, and other specific conditions. The design practices have been built-up over many years, sometimes based on full-scale testing, and sometimes validated by many years of fire loss data. The standardized procedures are adequate for most commonly encountered situations, only requiring expert modification for relatively few special circumstances. Technical reference books are available to support the design community. Industries exist to produce reliable equipment and to regulate the manufacture of such equipment. This technical infrastructure does not yet exist for water mist fire suppression systems. Some practical procedures to direct the design of water mist systems for pool fires and jet fires in enclosures are emerging, but much more research is needed to broaden the understanding of the relationship between fuel type, compartment features and spray system performance. Although sprinkler system design practices evolved over many years, there is a demand to produce a similar data base for a wide range of applications for water mist systems as quickly as possible. The best way to build such a technical base quickly is, therefore, to combine the coordinated efforts of all research groups.

A research project at the National Fire Laboratory, presently in progress, is aimed at investigating the engineering factors that must be understood in order to design a water mist fire suppression system for shipboard machinery spaces. This research program, which is jointly funded by the Canadian Navy (National Defence) and the National Fire Laboratory, has involved testing of water mists in obstructed spaces, including fire suppression tests in a mock-up of a shipboard machinery space. A number of practical engineering factors that have been identified as part of the development work necessary to bring these systems into the mainstream of fire suppression design are summarized in this paper. These include: defining the fire hazard and the fire safety objective; specifying the characteristics of fine sprays; exploring cost effective methods of producing suitable sprays and understanding their limitations; determining the spray flux needed to achieve the fire control objective for particular fire scenarios; accounting for the effects of obstructions and ventilation on spray density and distribution. This paper does not attempt to provide solutions to the engineering questions that have been raised. The objective is to sketch out the nature of each problem, and to suggest possible directions for resolution.

Defining the Fire Scenario

As in any fire suppression system design, the fire scenario must be well defined so that factors such as minimum nozzle discharge and spray flux density, nozzle location and spacing, minimum spray duration and probable degree of fire control can be determined. The fire scenario will depend on the fuel type and configuration, and the compartment conditions, such as:

Fuel Type:

- Combustible/flammable liquid - spill and pool fires
- Pressurized liquid jet
- Gas jet
- Class A combustibles, including plastics
- Electrical or electronic equipment

Fuel Configuration:

- Pool fire at floor level
- Jet fire at floor, mid-height, or ceiling level
- Class A combustibles, at floor, mid-height or ceiling level, low or high piled, loose or dense
- Electrical equipment in cabinets, cable trays

Compartment Conditions:

- Compartment dimensions
- Open or closed compartment
- Obstructions, localized or dispersed
- Shielded fire
- Ventilation factors affecting air movement
- Damageability of contents

These three factors of fuel type, configuration and compartment conditions, combine to define the nature of the fire and set the conditions under which it can be extinguished or controlled. For example, the fuel type will determine the heat release rate and potential fire duration. The fuel configuration, i.e., dispersed throughout a space, in piles, on racks, on surfaces, or inside cabinets, will determine how fast the fire grows and spreads. Both the type of fuel and its configuration influence whether it will be a flaming or smouldering fire. Compartment conditions such as ventilation and size determine the intensity of heat radiation reflections from surrounding surfaces to the fuel, the velocity of the fire plume, the rate of deepening of the hot gas layer, and the manner in which a fire suppressant can be distributed in the space. The compartment also physically limits the placement of detection and suppression system components. Finally, the vulnerability of the contents of the compartment to fire damage determines how fast the system must operate and the degree of control that must be achieved.

The experience base for mist systems, so far, applies to only a few of the possible fuel types, configurations and compartment conditions. Of the fuels, flammable/combustible liquid pool fires and liquid fuel jet fires, and to a lesser extent gas flares, have received the most attention. Water mist systems are being suggested for fires in ordinary cellulosic (Class A) combustibles such as bedding and foam mattresses, as has been demonstrated in recent tests conducted in Sweden in conjunction with the Marioff company. Fire in wood and plastics usually develops a char layer which reacts quite differently to spray than an open flame above a pool fire (personal communication, Fire Research Station, UK, 1992). The potential use of water mist systems for smouldering fires in electrical cables and in electronic circuit boards is of interest to many, but not much has been done to test the suitability of water mist for these types of fuels. With respect to the compartment conditions, the experience base is strongest for naturally ventilated compartments of small to moderate size, with a minimum number of obstructions.

It is important to understand how the fuel, its configuration and compartment conditions combine to determine the fire scenario, because those same factors also influence how the water mist system will perform. The mechanism by which water spray acts to extinguish flame appears to be the result of a combination of factors, including heat extraction due to rapid evaporation of fine drops, oxygen displacement due to steam displacement of air, and attenuation of the radiant heat feedback loop between flame and unburned fuel. The relative importance of one or the other factor is influenced by the type of fire (flaming or smouldering), its stage of growth, and the degree of enclosure. For example, it has been demonstrated that water mist can extinguish pool fires in both enclosed and unenclosed conditions. Steam displacement of oxygen may be significant in the case of an enclosed fire, but less so in the case of an enclosed fire. Attenuation of the radiant heat feedback and heat extraction would be of greater significance in the case of the unenclosed fire. In enclosed fires, if the fire is incipient and the compartment temperature is low, there may be very little steam produced when the spray activates, so that steam displacement again will not be the primary mode of extinguishment. If the spray had been discharged into a hotter compartment, steam displacement would dominate the suppression event, however.

These examples serve to illustrate that the performance of the water mist system itself and the expected level of fire control are dictated by the type of fuel, its configuration and the compartment conditions. It is not yet possible to set design criteria that are applicable to the full range of fuels, fuel configurations and compartment conditions for which water mist systems are being considered. Generalizable design criteria will emerge as the experience base grows, case by case, application by application.

Defining the Fire Safety Objective

Having identified the fire scenario, the designer of a water mist system must set realistic criteria by which to judge the success of the system. The expected outcome of operation of a standard sprinkler system is reasonably well defined – either it extinguishes the fire or limits fire size, burning rate and room temperatures to minimize the potential for harm. The expected outcome of operation of a water mist system is identical, with some additional possibilities. For water spray systems for the aircraft post-crash fires, for example, the objective is not to extinguish the fire, but to attenuate radiant heat from an external pool fire and provide cooling, to provide an additional 2 or 3 minutes time for the occupants to escape (Hill 1992). Where it is intended to use a water mist system to replace a halon system, the intended performance of the system will inevitably be compared to the performance of a halon system. It may be that, where the halon would have completely extinguished even a shielded fire, the water mist system might not be able to achieve complete extinguishment. Various compensating factors will affect the final comparison, however, such as more rapid temperature reduction due to the superior cooling effect of water mist, less restriction on compartment tightness, earlier re-entry, and so on. In other words, the fire safety objective of the water mist system should be consistent with the attributes of water mist. The fire scenario, and the fire safety objective, then, define the starting point for effective engineering design of a water mist fire suppression system.

Characteristics of Water Sprays for Fire Suppression

A full discussion of how to characterize atomized sprays in general is beyond the scope of this paper. The reader is referred to the text "Atomization and Sprays" by Arthur H. Lefebvre for an authoritative, comprehensive presentation of the subject. Lefebvre presents the basic science for sprays for a myriad of applications, from paint sprays to fuel sprays in combustion chambers. For the purpose of developing engineering methods for design of water mist fire suppression systems, however, certain fundamental principles must be discussed. In regard to the characterization of sprays, then, four factors are needed to properly characterize a water mist for fire suppression purposes. These are:

Drop size distribution (diameter and range)
Spray flux density
Spray angle
Spray projection

Drop Size Distribution

Researchers commonly define a spray, for casual comparisons at least, by stating a single statistically-defined mean diameter, typically the Volumetric Mean Diameter (VMD), or the Sauter Mean Diameter (SMD). Representative mean diameters can be defined in terms of simple diameter, droplet surface area or volume. For example, the VMD, (also referred to as the Mass Mean Diameter (MMD), and notationally as $D_{V0.5}$), means that 50 percent of the total liquid volume is in drops of smaller diameter. The SMD is the volume/surface area mean diameter. If a single representative diameter is used, the same spray could be described using the SMD as an "80 micron spray," or using the VMD as a "100 micron spray," depending on the speaker's choice. The choice of representative mean diameter depends on the application being studied, and different engineering disciplines have different preferences. The SMD is used for mass transfer and reaction analysis. The VMD, however, is emerging as the preferred representative mean diameter for computer modeling of spray/fire interactions. An agreement to use one or the other for casual comparison should be established for fire safety engineering use.

To provide a better sense of the nature of a spray distribution, it is useful to plot the results of a drop size measurement as "Cumulative % volume" versus drop diameter. The resulting "S" shaped curve reveals the whole story, including the maximum size of drop and the range of drop sizes. If the whole curve cannot be provided, a minimum of three parameters can be used to give the same general information. For example, the three parameters $Dv_{0.1}$, $Dv_{0.5}$ and $Dv_{0.9}$, (i.e., the diameter for which 10%, 50%, or 90%, respectively, of the liquid volume is in drops of lesser diameter) describe the spray drop size distribution reasonably well. The stated range of drop sizes then includes both the SMD and the $Dv_{0.5}$ and gives a sense of the extremes of the spray. Figure 1 shows typical spray cumulative distribution plots for a pressure-type nozzle at different operating pressures and distances from the nozzle.

Insert Figure 1 about here.

For modeling the interaction of water mist and fire using computational fluid dynamics, the distribution of drop sizes in the spray is represented as a function of two parameters, one of which is a representative diameter and the other a measure of the range of drop sizes. Various empirical distribution functions are available: a Rosin-Rammler distribution, described in Lefebvre (1989), is used by many modelers at present. It can be computed easily from the data collected by widely used drop sizing instruments.

Although the differences between the VMD and the SMD may appear significant on paper, there are practical aspects of using sprays for fire suppression systems that make it of academic concern. For one thing, at the macro-scale of fire suppression mists, the unavoidable variation in experimental measurements may exceed the difference between the VMD or the SMD. Distinctions that are significant in atomized sprays in combustion chambers, measured a few tens of millimetres apart, are of less significance in large rooms, measured metres apart. Further, the devices used to measure drop diameters themselves may introduce differences in the representative means. Optical technologies that are available for drop size measurement include (but are not limited to) the Bete shadowgraphic video system, the Malvern laser diffraction instrument, laser Doppler anemometers, and phase/Doppler particle analyzers. Researchers are aware of the need to do comparative studies of the results of measurements taken on different instruments. A potential difficulty with comparative studies, however, will be ensuring that not only the particle size instruments are calibrated, but also the instruments to measure nozzle pressure and flow rate (Lefebvre 1989). Furthermore, it makes a tremendous difference where in the spray the drop size measurement is taken. The NFL research indicates that, in a downward-directed spray, drop size increases with distance from the nozzle as the differences between the velocities of individual drops reduces, and drops collide and agglomerate. In a horizontal spray, drop size increases with both vertical and horizontal distance, up to the point where larger drops have fallen out of the spray and only the finest fraction remains drifting in the air. Measurements taken 0.4 m from a nozzle will, for example, show a 100 micron $D_{V0.5}$, but at 1.6 m from the nozzle, a VMD of 200 microns. There is often a similarly wide variation in the VMD at different points radially within the spray. With all of the possible variations in measurement technique and macro-scale conditions, it appears unrealistic to be concerned about distinctions finer than 50 microns in comparing sprays. There is, nonetheless, great utility in using a single representative diameter to describe a spray; it is important to appreciate the limits of precision to the measurements, however.

It is in the well-mixed spray distributed throughout a large compartment that evaporation, heat transfer and radiation attenuation occur, which result in suppressing a fire. After the spray leaves the nozzle and interacts with other spray jets and obstructions in the space, the spray distribution will bear little resemblance to the spray distribution measured under laboratory conditions close to the nozzle. Figure 2 shows the difference between the spray distribution for a single nozzle measured close to the tip, and for several nozzles of the same type, measured at mid-height in the middle of the obstructed room. From a single nozzle operating at optimum pressure, the spray starts out with drop size parameters $D_{V0.1}$ and $D_{V0.9}$ between 50 and 142 microns, with a VMD ($D_{V0.5}$) of 92 microns. But at mid-height in the room, with many nozzles operating, the mixed spray has drop diameters ranging from 140 to 380 microns, with a $D_{V0.5}$ of 230. The difference is due mostly to the agglomeration of drops as they move turbulently in the compartment. It is the blended, agglomerated spray that is transported by convective currents around the room, cools the gases in the fire plume, penetrates into shielded areas, and interacts with the fire.

Insert Figure 2 about here.

It is not an easy matter to predict, from the bench test distribution curves of individual nozzles, the drop size distribution of the combined spray inside a particular compartment. It could possibly be done using computational fluid dynamics models, validated with relatively easy-to-take drop size measurements. More work is required in this area.

Spray Flux Density

Flame suppression with fine sprays requires that a certain minimum mass of water droplets be suspended as spray. Therefore, a spray must have a density, or mass flow rate, that is appropriate for the fire scenario and compartment conditions. Whether the extinguishment mechanism is due to heat extraction as fine droplets evaporate, to displacement of oxygen by steam expansion, to radiant heat feedback attenuation, or a combination of all three effects, a certain minimum number of droplets per volume of space will be required to accomplish suppression. Determining what spray flux densities are required for particular fire scenarios will be the primary subject of research into water mist suppression systems for at least the next decade. For this discussion on the desirable characteristics of sprays for fire suppression, it is intended only to point out that the volumetric output from the nozzle and the uniformity with which that volume is distributed in space, are important factors.

Selecting full cone, rather than hollow cone, spray patterns allows us to assume that the spray will at the outset be relatively uniformly distributed. Next of concern is the actual mass flow rate of water through that spray volume. The initial spray density must be high enough to allow for losses of spray due to drops falling out or depositing on the surfaces of obstructions, and still have enough suspended water particles per unit volume of air to be able to extinguish a fire. For example, some nozzles produce a very fine spray (with drop sizes ranging from 50 to 100 microns, for example), but the volumetric flow rate may be less than 3 Lpm. Depending on the size of the compartment, the distance the spray has to travel to reach the fire, and the total area of obstructing surfaces, it is likely that not enough droplets will survive the losses and be available to suppress the fire. The flow-through of 3 Lpm might be quite adequate for a small, unobstructed compartment, but inadequate for a larger, or heavily obstructed, compartment. Thus, a nozzle must have not only the desired drop size distribution, but a total mass discharge rate appropriate for the geometry of the compartment.

The matter of describing the density of water mist warrants discussion, and further research. Drop size distribution measurement systems, conforming to ASTM E-799, report drop concentration or flux density when possible, usually in units of cm^3 of water per cm^3 of sample volume ($\mathbf{F_d}$). The flux density is computed using the measured frequency counts, the computed volume per drop assuming a spherical shape, and the volume of the measurement field (which is instrument dependent). In the NFL experiments, measurements of droplet concentrations ($\mathbf{F_d}$) in sprays of comparable appearance varied widely, ranging from $5 \times (10^{-5})$ to $5 \times (10^{-7})$ cm^3 per cm^3. It was suspected that the wide variation in volume density measurement for otherwise comparable sprays was due to very localized differences in the spray. At this stage, then, the drop/volume concentration obtained as part of the drop size measurements was not considered to be a practical parameter for characterizing spray density.

Another way to visualize spray concentration is to compute a theoretical average density over the entire volume of the compartment, or $\mathbf{D_v}$. This is done by dividing the total volume flow rate (Q in Lpm) of the nozzles by the volume of the compartment, without regard for the volume occupied by internal objects:

$$\text{Avg. Density per unit volume } \mathbf{D_v} = Q_{total} / V_{total} \qquad [\text{Lpm/m}^3] \qquad (1)$$

Applied in the case of a total flooding system, this approach implies that the spray is uniformly distributed throughout the enclosure. In fact, there may be large differences, depending on the number and size of objects in the room, the location of the nozzles and the geometry of the room. The average density so calculated may be quite different than the local density that actually extinguishes flame. For example, density will be higher near the floor than near the ceiling. Expressing spray density as mass per unit volume is appealing, however, because it corresponds to our expectation that that is the most appropriate measure of ability to extinguish fire. It is also the form that is useful for computational fluid dynamics modeling, which considers the mass of water droplets per control volume. For practical reasons, however, it is difficult to actually measure localized spray density in volume/volume units. A full discussion of the difficulties associated with such a measurement is beyond the scope of this paper.

A simpler way to characterize spray density is to use the traditional means of characterizing sprinkler spray density, i.e., total flow rate per unit area:

$$\text{Avg. Area Density, } \mathbf{D_a} = Q_{total} / A_{total} \qquad [\text{Lpm/m}^2] \qquad (2)$$

Density expressed in this way can be measured by collecting spray on sample surface areas, over a known time interval. Because it can be relatively easily measured, it is in our opinion the most practical way to talk about the density characteristic of a spray. Although it is a feature that can be quantified, it is nevertheless one step removed from the real physical condition that is involved in the interaction of spray drops with hot gases or flame.

Notwithstanding the uncertainty mentioned earlier about the variability in the spray flux density readings obtained using the drop size analyzer ($\mathbf{F_d}$), it is of interest to convert $\mathbf{F_d}$, in units of cm^3 per cm^3, to Area Density, $\mathbf{D_a}$, in Lpm/m^2. To do this, the velocity of the spray must be known or estimated. Assuming that the spray is uniformly distributed throughout a volume with a cross-sectional area of 1 m^2, has a uniform velocity across the entire cross-section, and that 1 cm^3 of water weighs 1 gram:

$$\mathbf{D_a} = 60{,}000\ (\mathbf{F_d})\ (\mathbf{v}) \tag{3}$$

$\mathbf{D_a}$ = Area Density as would be measured on a collection surface, [Lpm/m^2]
$\mathbf{F_d}$ = Flux Density from drop size measurements, [$cm^3/cm^3 = g/cm^3$]
$\mathbf{v}$ = average spray velocity, assumed to be uniform, [m/s]

For example, for an $\mathbf{F_d}$ reading of 5.0 (10^{-5}) cm^3/cm^3, and a spray velocity of 5 m/s, the estimated equivalent average $\mathbf{D_a}$ would be 15 Lpm/m^2.

Using the terminology of standard sprinkler design, we would like to be able to relate the Actual Delivered Density (ADD) to the Required Delivered Density (RDD) for a particular fire scenario. The experimental basis for determining RDD's for fine sprays is just beginning. Some information has been acquired for unobstructed pool and liquid jet fires. For example, in the NFL's work involving pool fires in obstructed machinery spaces, average densities of 3.0 Lpm/m^2 from a network of 18 ceiling nozzles completely extinguished pool fires 3.4 m below, depending on the degree of obstruction. Even lower overall densities were successful if nozzles were located closer to the fire, under the bilge decks. If complete extinguishment is not the objective, it is believed that control over temperatures in the room could be achieved at lower densities. However, much more research is needed to build the data base for a wider range of compartment conditions. The effects of obstructions and convective air currents on determining the ADD have yet to be quantified, and again, much research is needed.

Neither the average flow rate per compartment volume, nor the average flow rate per total floor area, is a particularly good way of quantifying the spray density needed to extinguish a fire. It is probably the localized density in relation to the fuel source that is most important. As an example, in an obstructed shipboard machinery compartment with a pool fire in a bilge area under deck plates, a few nozzles placed below the deck plates will bring about rapid extinction, because they direct a relatively high spray density directly into the flames, while a much lower spray density from ceiling nozzles is all that is required to cool the room.

Spray Angle

The spray angle is more a characteristic of the nozzle than the spray, but it is nonetheless important to understand its significance in defining appropriate sprays for fire suppression applications. Spray angle directly affects the velocity and direction of the droplets leaving the nozzle. Therefore, for modeling with computational fluid dynamics at least, the range of directions of initial droplet trajectories is of interest. Spray angle is a critical factor in determining nozzle spacing to ensure a relatively uniform distribution of spray, without large void areas between nozzles. Finally, spray angle is very significant in determining the initial velocity and momentum of the spray, which in turn determines its ability to penetrate obstructions in the compartment.

Spray Projection (Kinetic Energy)

The ability of the spray to get past obstructions in the compartment, and to interact with the flame of a fire, depends on the kinetic energy provided by the nozzle. Considering only the mass of the spray (and not the entrained air), kinetic energy is defined as:

$$\mathbf{KE} = \frac{1}{2} \mathrm{M} \bullet \mathbf{v}^2 \tag{4}$$

$\mathbf{KE}$ = kinetic energy of the spray
M = mass of unit volume of spray plus air, g
$\mathbf{v}$ = mean velocity of a unit volume of spray, m/s

For comparable mass flow rates and drop size distribution, sprays with higher initial velocity in a particular direction will have higher kinetic energy than sprays with lower initial drop velocities. It is possible to derive an expression to calculate the average kinetic energy per cubic metre of spray (**KE/m^3**), using the volume flux density obtained from the drop size analyzer ($\mathbf{F_d}$), and a measured velocity of the spray:

$$\mathbf{KE/m^3} = 10^6 \bullet \mathbf{F_d} \bullet \frac{\mathbf{v}^2}{2} \tag{5}$$

$\mathbf{KE/m^3}$ = kinetic energy of 1 m^3 of the spray
$\mathbf{F_d}$ = Flux Density from drop size measurements, [cm^3/cm^3 = g/cm^3]
$\mathbf{v}$ = average velocity of a unit volume of spray, uniform, [m/s]

Although equation (5) is theoretically appealing as a way to quantitatively compare the energy levels of spray, it requires special equipment to obtain both $\mathbf{F_d}$ and **v**, and is therefore of limited practicality. Without measuring either droplet size or net spray velocity, the kinetic energy of a particular spray can be at least qualitatively judged by comparing the horizontal projection of the sprays. The projection ability of the nozzle is partly determined by the spray angle, but also by the mechanism for producing the spray. Nozzles with a wide spray angle will have a lower projection than narrower spray angle nozzles. To maximize spray projection, higher nozzle pressures and reduced spray angles are needed. Higher pressures have an associated energy cost, and reduced spray angle will mean closer nozzle spacing; both factors therefore may involve a higher installation cost.

One way to keep water pressure requirements low and still achieve good spray drop size and high kinetic energy, is to use air-atomizing nozzles. The energy added by compressed air produces a good drop size distribution and imparts a high initial velocity to the spray, at lower water pressure than a "pressure-only" nozzle. The requirement to provide compressed air to every nozzle trades one cost for another, however.

Based on experiments at the NFL with pool fires in an obstructed compartment, an energetic spray with reasonably high projection has two advantages. The first advantage is that the percentage of spray that gets past obstructions increases, so that fewer nozzles are needed to achieve a sufficiently dense distribution of spray in the room. As noted earlier for obstructed spaces, the representative drop size increases as spray moves away from the nozzles. A spray with higher initial velocity will still have a finer spray distribution than a spray of initially lower velocity, after it has been modified by the obstructions. A spray with high energy will reflect from surfaces and continue to move in a turbulent fashion through the space. Reflected spray can move behind obstructions and around corners, thus permitting filling of the recesses of the compartment volume with spray using a minimum number of nozzles.

The second advantage of high initial kinetic energy is that extinguishment is greatly improved (for pool fires, at least) if the spray droplets penetrate the actual flame in a turbulent fashion. Turbulent mixing of flame and droplets resulted in rapid extinction, whereas quiescent surrounding of flame with mist was unable to bring about extinguishment. In order to penetrate the flame zone, the direction of the spray movement had to be at an angle to the flame plume. In several of the NFL tests in which the spray had a high energy, but in which its direction of movement was parallel to, and in the same direction as, the flame plume (co-current), the turbulence and additional air provided by the air-atomizing nozzles actually increased flame intensity. More research is needed to determine the minimum required spray density that actually penetrates the flame to cause extinction.

Spray energy that is very high creates rapid pressure changes in the compartment, which may force smoke and fuel out of the compartment. In some cases, excessive turbulence around the flame in a small space may accelerate burning. This occurred in some of the NFL tests when the direction of the spray was co-current with the direction of the fire plume.

Summary of Characteristics of Sprays

To characterize a fine spray suitable for fire suppression, it is necessary to describe more than a single representative droplet diameter. At least two parameters are needed, one to describe a representative diameter, and another to describe the range. Preferably, a plot of cumulative percent volume versus diameter should be provided. Various empirical distribution functions (such as Rosin-Rammler) are used to input the drop size distribution into computational fluid dynamics model codes.

The drop size distribution measured very close to the nozzle will be much finer than when measured at a distance from the nozzle. Interaction of spray with adjacent spray cones and obstructions results in agglomeration of drops, so that the VMD of the spray in the midst of a space flooded by fine spray may be as much as 100% larger. The range of drop sizes will increase as well.

Spray density is very important for fire suppression, although as yet it is difficult to relate actual delivered density to required delivered density for different fire scenarios. Expressing density as average density per unit volume in a total flooding system, using the total flow rate and the total compartment volume, is only useful for basic comparisons, because of large differences in localized densities. Traditional measurement techniques for fluxes, in volume flow per minute per unit of floor area, are easier to obtain but are not very useful for computational fluid dynamics modeling. Neither volume flow rate per volume, or volume flow rate per floor area, are particularly relevant to either actual delivered or required delivered densities. It is probably much more important to understand and have control over the localized densities in relation to the fuel source than to quantify spray density of broadly average terms.

Spray angle and spray momentum are factors that influence nozzle spacing, and the ability of the spray to fill the compartment volume in spite of obstructions. Sprays with high momentum interact turbulently with the flame, and appear to improve extinguishment.

Methods of Producing Sprays (and their Limitations)

For the NFL experiments, it was practically possible to achieve a spray with good appearance, projection and flow rate, with an initial drop size distribution from a single nozzle operating at optimum pressure with parameters $D_{V0.1}$ and $D_{V0.9}$ between 50 and 142 microns, with a VMD ($D_{V0.5}$) of 92 microns (see Figure 2). Spray drop size distributions in this range can be produced practically, for fire protection purposes, using impingement nozzles, moderate to high pressure nozzles, or air atomizing nozzles.

Impingement nozzles position a deflector, either a single probe, plate or a specially shaped spiral, in front of the orifice, so that the high velocity jet strikes the deflector and breaks up into a spray. Pressure nozzles rely on water pressure to force water through one or more small orifices or at a high velocity, so that the jets breaks up into fine droplets. Air atomizing nozzles inject compressed air into a high velocity water jet or sheet and cause it to break up into fine spray. Each type has advantages and disadvantages. Practical considerations relating each type are presented below.

Impingement Type Nozzles

The impingement-type nozzles produced coarser sprays than the other types of nozzles examined in the NFL tests. For the smallest nozzle tested, the spray had a high pressure requirement, low volumetric flow rate, and poor projection, although the initial drop size distribution of $Dv_{0.1}$, $Dv_{0.5}$ and $Dv_{0.9}$ of 75, 125 and 200 μm, respectively, was reasonable. The orifice was prone to plugging, and the deflection pin was easily bent by water-borne debris. Once the deflection pin was bent, suitable spray-production was no longer possible.

More robust impingement nozzles with spiral-type deflectors produced more energetic sprays, with reasonable projection and substantial flow rates. The drop size distributions at moderate working pressures (550 kPa (80 psi)) tended to be too coarse, however, with at best $Dv_{0.1}$, $Dv_{0.5}$ and $Dv_{0.9}$ of 280, 350 and 410 μm, respectively. The higher number of larger drops would be a disadvantage for suppressing pool fires, as they could cause splashing. The impingement nozzles were rejected for further testing in the NFL tests in favour of nozzles with equivalent flow rates but finer spray distributions. Nevertheless, spiral type nozzles are robust and simple in design. If the spray distributions were improved, they could be suitable for some applications of water mist fire suppression systems.

Pressure-Type Nozzles

Generally, it is less costly to design, operate and maintain a pumping/piping system that operates at low pressures rather than at high pressures. Depending on design, commercially available moderate pressure-type nozzles may require pressures between 550 and 690 kPa (80 and 100 psi) to produce a reasonably fine spray with the appropriate flux density and kinetic energy. The SSC 3/4 7G-5 nozzle is an example (see Figure 1). Although this nozzle has a reasonably fine initial drop size distribution, wide spray angle and good projection, its volume flow rate at 550 kPa is nearly 30 Lpm (8 gpm). If used in a total flooding system, the cumulative flow and pressure requirements may be excessive. For example, for a compartment requiring 10 nozzles to provide the desired spray distribution, the combined flow for a total flooding system would be typically 330 Lpm (87 gpm), allowing 10% for "overage." With a starting nozzle pressure of 552 kPa (80 psi), allowing 69 kPa (10 psi) for elevation head and 200 kPa (29 psi) for pipe friction losses, the final pressure requirement at the pumping source could be as high as 821 kPa (119 psi). This flow/pressure demand of 330 Lpm at 821 kPa (87 gpm at 119 psi) is just within "normal" fire suppression system pumping and piping practices.

To protect a larger compartment requiring more nozzles, the capacity of a "normal" fire suppression system would quickly be surpassed. Furthermore, because the flow rate is high, the total amount of water pumped into a closed compartment over the discharge time accumulates rapidly. At 330 Lpm (87 gpm) for 5 minutes, a total of 1650 litres (435 gal) would be pumped into the enclosure. For a shipboard application, such a high weight addition would be undesirable. It is suggested therefore, that there is a practical upper limit to the size of compartment that can be protected using such nozzles in a total flooding configuration. It may instead be necessary to divide a large compartment into sub-zones, so that only the nozzles surrounding the fire operate. Such a design approach would require appropriate detection/activation technology, and the operation of enough nozzles to surround the fire with spray. Whether zoned operation of a water mist system is feasible will depend on the specifics of the fire scenario, detection system capabilities and the control objectives.

High pressure nozzle systems generally have an associated cost in equipment and maintenance that make them less cost-effective than low pressure systems. There is an economic incentive, then, to operate the water mist system in pressure ranges achievable using standard fire protection pumping equipment. High (ultra-high) pressure nozzles, such as the Marioff nozzle, require specialized pumping equipment and distribution piping. Nevertheless, good spray drop size distribution, high spray energy, low overall flow rates and the potential to electrically activate specific nozzles, may combine to still produce a cost-effective system. Again, the maximum size of a total flooding installation may be limited by the pumping capacity and the tolerance of the compartment for total water accumulation. For very large compartments, partial activation of zones within the space must be considered. Further research is needed to determine the design parameters of such zoned systems in large compartments.

Air-Atomizing Nozzles

Air-atomizing nozzles have the advantages of good drop size distribution ($Dv_{0.5}$ ~ 100 μm) and higher spray velocity at reasonable water and air pressures. Because the orifices are not as small as in pressure-type nozzles, there is less concern about plugging with foreign matter. The NFL tests demonstrated that air-atomized spray nozzles requiring 414 kPa (60 psi) water pressure, and 550 kPa (80 psi) air pressure were most effective at penetrating obstructions. It was therefore possible to install nozzles at ceiling level in an obstructed compartment, and extinguish pool fires in the bilge area, without having to install separate nozzles to protect shielded areas below the deck plates. For moderate-sized enclosures, where compressed air is available, air-atomizing nozzles can be cost-effective.

There are several disadvantages of air-atomizing nozzles. These include:

1. The total air flow demand of a system involving multiple nozzles can be very high. The compressed air may be supplied from plant compressor systems, or from dedicated cylinders of compressed air or nitrogen. As an example, the air-atomizing nozzle used in the NFL tests (Spraying Systems Company (SSC) 1/2J-SU89) required 53 Standard Cubic Feet per Minute (SCFM) of air when operating at 380 kPa (55 psi) water pressure and 503 kPa (73 psi) air pressure; the nozzle discharge rate was 6.3 Lpm (1.7 gpm). For a 6 m x 6 m x 3.6 m high room with 18 nozzles operating to provide an average density of 3.2 Lpm/m^2, the total air demand was 954 SCFM. Depending on the degree of obstruction covering the bilge space, it typically took 1.5 to 5.5 minutes to extinguish the test fires. Assuming minimum five minute operation of the system at an air demand rate of 954 SCFM, a substantial reservoir and compressor system is required. If high-pressure gas cylinders are used instead of a plant air system, a large number would be required for a single operation. The system would subsequently be out of commission until the cylinders were replaced. The cylinders would occupy wall space and would add considerably to the total weight of the suppression system. These factors indicate that there is a practical limit to the maximum size of a total flooding system using air-atomizing nozzles.

2. The installation of piping for air in addition to the water piping increases the system cost in labour and materials, as well as weight and maintenance. To reduce those costs, improvements in the design of air-atomizing nozzles are needed to facilitate the installation of multiple nozzles into a gridded piping system, with a minimum number of fittings.

3. Design of air and water distribution piping for the air-atomizing system requires that both hydraulic and pneumatic calculations be performed to determine the total air and water demands, and to optimize the pipe sizing. To do this, the air and water discharge rates from a nozzle must be determined at different combinations of air and water pressure. The documentation provided by air-atomizing nozzle manufacturers seldom presents the pressure-discharge information in a manner suitable for performing the hydraulic/pneumatic calculations. Manufacturers should provide plots of liquid and air discharge rates versus air to liquid ratio (Qw and Qair versus ALR). Figure 3 shows the type of information needed to allow both the hydraulic and pneumatic calculations to proceed. Both curves can be characterized by a best fit equation, for use in standard calculation software.

Insert Figure 3 about here.

Effects of Additives on Spray Characteristics

To this point, the nozzle has been viewed as the primary factor influencing the spray characteristics. The properties of the liquid also play a role, however. It is clear from theoretical considerations of spray development that the viscosity, surface tension and density of the liquid will effect the break-up of jets or sheets into drops. For fire suppression purposes, "pure" water is the usual liquid. There are instances, however, when it is desired to use additives in the water, such as surfactants, foaming agents, or anti-freeze, or to use other than "pure" water, such as salt water. To determine whether these additives had an adverse effect on the spray characteristics, several tests were conducted as part of the NFL experiments. Nozzle performance was measured and compared using fresh water, salt water (2.5% by weight, the salinity of sea water), and a low percentage (0.2%) of foaming agent (AFFF).

Figure 4 shows that neither additive had a significant effect on the nozzle discharge characteristics. For hydraulic calculations, then, the effect of the additives was considered to be negligible. Figure 5 shows the drop size distribution curves for the air atomizing nozzle with and without the additives. The additives tended to increase the number of large droplets, as evidenced by the increase in the $D_{V0.9}$ from 140 µm to 170 µm for salt, and

200 µm for AFFF. The finer fraction of the sprays was not significantly changed. As was shown in Figures 1 and 2, however, the variations in drop size distribution due to variations in nozzle pressure and encounters with obstructions in the space are generally much larger than the increase in $D_{V0.9}$ caused by the additives. For practical purposes, the effect of the additives on drop size distribution was considered to be negligible in comparison to other factors affecting drop size distribution in large compartments.

Insert Figure 4 about here.

Insert Figure 5 about here.

Summary of Methods of Producing Sprays

For all three types of spray nozzles, there are practical limits to the size of compartment that can be protected by a total flooding type of system. Although the discharge from individual nozzles is less than a standard sprinkler, the cumulative discharge from a network of nozzles still represents a significant volume of water. Also, the pressure required for optimum operation of a single nozzle, whether of the pressure-only or the air-atomizing type, is significantly higher than for standard sprinklers. The total pressure demand for a water mist system may therefore surpass the capacity of regular fire protection water supplies, possibly requiring additional pumping capacity. A moderate pressure boost can usually be achieved without excessive cost, however, given that the water flow rate is low. On the other hand, the air-flow requirements for air-atomizing type nozzles are quite substantial, and will quickly limit the cost-effectiveness of large total flooding systems using such nozzles. The zoning of water spray systems within a large compartment, coupled with sophisticated detection/activation equipment, presents an alternative to a total flooding approach. More research is needed to determine the performance limits of such a system.

For small compartments and equipment enclosures in which only a few nozzles are required, any of the three types of mist-making nozzles could be applied. Both pressure-only and air-atomizing nozzles are capable of producing sprays with good drop-size distribution, volumetric flow rates, spray angle and spray projection.

Spray Flux Densities Required for Suppression

A great deal of work has been done over the last 40 years aimed at answering the question of what minimum application rate of spray is needed to extinguish a fire. One hypothesis relates the ratio of spray volume to flame volume, concluding, for example, that a flame will be extinguished if the water mist occupies 10 percent of the flame volume. Others have suggested that there is a relationship between the percent reduction in radiant heat energy and the probability of extinction for a fire engulfed by water mist (Fire Research Station, UK personal communication 1992). Other research has shown a relationship between the mass flow rate of a gaseous fuel and the mass flow rate of water droplets entrained in the fuel jet (Evans & Pfenning 1985). Wighus (1992) has shown a relationship between the total heat generated by the fire and the amount of heat absorbed by the spray, i.e. a Spray Heat Absorption Ratio, or SHAR. For example, when the SHAR approaches 0.6, pool fire flames will be extinguished. It is not the object of this paper to discuss the literature on this important subject. The NFL experiments have not yielded information to confirm or deny any of the suggested relationships. The experiments did, however, provide practical information about the effects of various compartment conditions on spray density, and the effects of the water spray on conditions created by the fire in the compartment. It is these observations, and their implications for the engineering design of spray systems in general, that will be discussed here.

The terms Required Delivered Density (RDD) and Actual Delivered Density (ADD) have already been introduced. The research, previously mentioned, to determine the minimum spray density required to accomplish extinguishment, was directed at determining the RDD. The RDD depends on the type of fuel and its arrangement; the type of fire - flaming or smouldering, small or large; the ventilation conditions in the compartment; and the fire safety objective. The ADD depends on the performance and location of spray nozzles; the degree of obstruction in the compartment; the ventilation conditions; the intensity of the fire; and the strength of fire-induced convective air-flows. Measurements of ADD of fine spray under fire conditions in compartments containing obstructions and shielded areas have not yet been made.

Full-scale fire testing using fine spray has demonstrated that it is easier to extinguish a large, flaming fire than a small flaming fire. In the NFL tests involving a 2 MW pool fire in a compartment with limited ventilation, the rapid flaming fire lowered the oxygen concentration in the room to below 15 percent at the time of activation of the spray. Extinction of the fire in the bilge area below deck plates was rapid, regardless of the degree of obstruction presented by the deck plates. It is surmised that the low oxygen levels, coupled with increased evaporation of spray and subsequent steam displacement, worked in concert to extinguish the fire. On the other hand, with a smaller fire of 600 kW and the same ventilation conditions, the fire took longer to extinguish, and the degree of deck plate obstruction mattered. Again, it is surmised that the relative importance of the different extinction mechanisms changed, according to the size of the fire. For the smaller fire, there was a greater need to have spray interact with the visible flame, where it could extract heat and act as a barrier to the thermal feedback to the fuel surface. For the larger fire, steam displacement of oxygen reduced the need for direct spray-flame interaction.

What are the general implications of the observed phenomena for design of water mist fire suppression systems? It is counter to traditional fire safety engineering practice to allow a fire to get big before attacking it; such an approach might be tolerable under some circumstances, but not usually for the type of facility presently protected with halon, for which water mist is considered to be a potential alternative. A more appropriate strategy for an automatic suppression system would be to design with the intention of extinguishing the fire while small. This means that nozzles should be located so as to maximize the probability that spray will interact with the flames. Applying this strategy in the case of the compartment studied in the NFL experiments, the recommended design would call for spray nozzles below the deck plates, in spite of the fact that under certain circumstances the fire can be extinguished using ceiling nozzles alone. In other words, high localized spray densities in the vicinity of the fire source are recommended. To achieve this, strategic location of nozzles based on the potential fire surfaces might be more effective than locating nozzles to provide uniform density throughout the compartment. Furthermore, strategic location of nozzles closer to the fire source means that the spray cloud will consist of finer drops than would be the case for water mist descending from ceiling nozzles. With this scenario, the spray density applied from ceiling nozzles can be kept quite low, and still be very effective at extracting heat from the fire gases, and preventing radiant heat damage to objects in the compartment.

This line of reasoning illustrates the advantages of general versus local spray application, but sheds little light on the magnitude of the spray flux needed to achieve extinction. In the NFL experiments, it was not possible to determine the minimum required density accurately, partly because of wide variation in the results of the full-scale tests. Also, it was not possible to measure spray flux density in any way that would determine the mass of water per unit volume actually arriving at the flame front. As illustrated in principle by Figures 1 and 2, the spray drop size distributions changed significantly as the spray moved through the compartment. Thus, any relationships between average flux densities expressed in terms of flow rate per compartment volume or floor area, and what was occurring at the flame front, were unreliable. More testing would be required, but under laboratory conditions that allow for more control over variables than is possible in full- or even intermediate-scale testing. In practical terms, however, fire suppression systems are never designed for minimum water application rates determined under ideal conditions. The initial spray density provided by the spray system must be high enough to overcome losses to interior surfaces, and to compensate for less-than-perfect correspondence between spray direction and the fire source. The movement of fine spray throughout the shielded portions of a compartment depends on highly variable forces such as the kinetic energy of reflected sprays, ventilation and fire effects.

Subject to the limitations on their significance just described, extinctions were achieved in the NFL tests with average spray densities as low as 3.0 Lpm/m^2, or 0.83 Lpm/m^3, calculated using the combined flow from ceiling nozzles averaged over the entire compartment floor area or volume. The time from spray-on to extinction of the last flames ranged from 1 minute to 3.5 minutes in tests that were considered to be successfully extinguished. Although the actual extinction of the last remaining small flames took several minutes, flames were reduced to small localized areas very quickly, and maximum ceiling temperatures were reduced to less than 65°C within 45 to 90 seconds in almost all cases. The fastest extinctions occurred where nozzles were placed below the bilge deck plates, in which case spray was able to impact directly on the flames, with no ceiling nozzles operating at all. The average localized density below the bilge decks, calculated based on the floor area "covered" by individual nozzles, was nearly 4.5 Lpm/m^2. Based on the volume "covered" by each nozzle in the 1 m high bilge area, the volumetric flux density was 4.5 Lpm/m^3.

The Effects of Obstructions on Spray Density

Every surface engulfed in a cloud of spray will become coated with water, and will extract water mass from the spray as it goes by. Obstructions "scrub" the spray from the air; this phenomenon is used to advantage in industrial scrubbers intended to remove aerosols and mist from emission stacks discharging from industrial processes. Obstructions reduce the velocity and momentum, deflect and cause changes in direction of the spray. As a result, in designing a water spray suppression system for a heavily obstructed compartment, it is extremely important to take the obstructions into account.

It has been imagined that fine water mists would act in the same way as gaseous suppression agents, and move freely into all recesses of a compartment to the seat of the fire, and extinguish it. To a certain extent, this is true; some mist transports itself into all parts of a compartment. Unlike gaseous agents, however, the mass of water per unit volume of air reduces as it passes every obstruction. As has been previously described, the success of a spray in extinguishing a flaming fire appears to require that the spray have some momentum, to be able to push droplets into the interior of the flame. In the NFL experiments, 0.5 m diameter pool fires surrounded by fine mist with a momentum co-current (parallel) with the fire plume, continued to burn, in spite of the presence of the water droplets. This is consistent with the observation that it is possible for a person to stand in the mist-filled compartment without drowning. The fire was able to draw the oxygen it needed to continue burning from the mist. Only when the mist was able to push itself into the core of the flame, was it able to extinguish it.

Figure 6 shows the results of tests conducted to measure the effect of increasing degree of obstruction on the density of a horizontal spray moving through a 1 m x 1 m plenum. Each obstruction grid consisted of 6 horizontal tubes spaced approximately 150 mm apart vertically, with a total surface area of 0.83 m^2. Spray density was measured with a special collecting cone that averaged the mass flow rate per square metre over the height of the plenum. Spray density was measured with 0, 1, 2 or 3 such grids in the path of the spray. The figure shows that operating the nozzle at a very high pressure to overcome the obstructions was counter-productive. The increased turbulence and violence of impacts on the obstructions accelerated the reduction in spray density, so that after passing through 3 grids, the remaining flux density was only marginally higher than for the nozzle operated at a lower pressure. For the nozzle operated at a lower pressure, the spray flux density decreased by 16, 35 and 57 percent with 1, 2 and 3 grids, respectively.

Insert Figure 6 about here.

Obstructions in the compartment act to reduce both spray momentum and density. Under favourable circumstances, an obstruction might deflect the spray directly into a flame zone and improve extinguishment. Under less favourable circumstances, the loss in momentum will reduce the effectiveness of the spray. The conservative assumption must be that conditions will seldom be favourable. The way to compensate for obstructions, then, is to reduce nozzle spacing, increase initial spray energy, and look for strategically favourable nozzle locations. Although it would be convenient to be able to install ceiling mounted nozzles for all compartments, in the same way that standard sprinklers are installed, the design of a water mist system may require more detailed consideration of nozzle location.

Criteria for judging "strategic locations" include the projection capability of the nozzle, the spray angle and initial flux density, and the geometry of the obstructions. Nozzles may have to be positioned to project horizontally into some spaces in order to maximize the coverage volume, and to keep the spray direction parallel to, rather than orthogonal to, cable trays or ducts, for example. For large machinery compartments, it becomes impractical to use nozzles with horizontal projection distances less than 3 or 4 m, due to the economic disadvantage of having to install too many nozzles.

Ventilation Considerations

The NFL experiments demonstrated that extinction is easier when the oxygen concentration in the compartment is low. Where it is considered to use water mist as an alternative to halon, as for example, to replace an existing halon system, it can be assumed that the compartment is designed to have no leaks. In that case, the ventilation system is usually designed to be closed automatically upon receipt of a detector signal. This is a potential advantage from the point of view of suppression, because the same extinction capability may be achieved at a lower spray density than would be required in an open, fully ventilated compartment. Consideration must be given, however, to the feasibility of using air-atomizing nozzles for total flooding of closed compartments. It has already been described that air atomizing nozzles require substantial air flows - for example 50 SCFM per nozzle at 550 kPa (80 psi). Discharging air at that rate from several nozzles into a closed compartment will quickly pressurize the compartment. This has implications for potential smoke spread from the fire compartment into adjacent zones, either through dampers into the ventilation system, or through door or hatch openings made to allow entry into the space. A similar effect on room pressure may occur with high energy pressure-only type sprays, as a result of the spray momentum.

In facilities where smoke damage is of concern, a smoke extraction system may be provided for the compartment being protected. Upon receipt of a smoke detection signal, both the suppression system and the smoke extraction system may be activated simultaneously. As room air moves toward the exhaust inlets, increased air velocities could alter the distribution of water mist in the compartment. Such a possibility must be taken into account during the design stage, not only for the effect on the spray distribution, but also for the effect of the additional water in the extraction system duct work.

It is worth remarking that water mist systems have been demonstrated to operate very well on pool and jet fires in open compartments, and even fully in the open, i.e. outdoors. The success of the system depends more on the way in which the spray interacts with the flames, whether it enters the flame volume and extracts heat from the combustion process or blocks thermal feedback to the fuel surfaces, than on steam displacement of oxygen. There is probably no need to require that the fire compartment be cut off from combustion air, any more than such control over ventilation is required for standard sprinkler systems. The particular benefit of water mist systems may be that they effectively block radiant heat and cool the fire plume, so that fire, even if it is not fully extinguished, does not spread or cause excessive collateral damage.

Where fire is contained in an enclosure, activation of a water mist system causes some rapid pressure fluctuations. This phenomenon is well recognized by the fire service, as cases of windows imploding into a compartment upon application of a water spray are well documented. It is observed in the literature that when a spray is injected directly into the flame or hot gas layer, the rapid cooling causes a strong contraction and reduction in gas volume. The gas contraction is much greater than the expansion of steam as the droplets evaporate. This phenomenon was recorded in the NFL fire tests. A plot of room pressure versus time for a typical test is shown in Figure 7. Upon activation of the water spray from ceiling nozzles after a 90 second pre-burn time, the room pressure became strongly negative, -10 Pa or greater. A sudden negative ΔP of that magnitude could cause large windows to implode, depending on their size and strength. In tests conducted in the same room involving standard sprinklers, which have much coarser sprays than the fine sprays under consideration here, it was noted that the pressure reduction upon activation of the sprinklers was not so dramatic, and never went entirely into the negative pressure region. The exceptional cooling effectiveness of the very fine sprays is evident.

Insert Figure 7 about here.

In the NFL tests, the spray was activated after 90 seconds of free-burning. The fast-flaming pool fires had generally reached their peak burning rate in that time. Because of thermal inertia, however, objects in the compartment were just beginning to respond to the fire, and temperatures were not very high when the spray was activated. If the fire had burned for a longer time before activating the spray, the steel structures and all of the objects in the room would have been much hotter. For late activation of spray into a hot compartment, the rate of evaporation would be much greater than in the early-activation case, with the likely result that a steam explosion would occur. The need to deal with a fully developed or post-flashover fire in a compartment is more likely to be a matter for manual fire fighting. It should be assumed that water mist systems are intended to activate automatically early in the growth of a fire, so that very high compartment temperatures at time of activation are not an issue.

Concluding Remarks

The purpose of this paper has been to discuss a number of practical issues relating to the design of water mist fire suppression systems. There is presently a lot of interest among fire safety engineers in using water mist systems as an alternative to halon, on the basis that the mist will act like a gaseous suppression agent to fill all recesses of a compartment. Although there is a growing confidence that water mist systems can successfully extinguish or control flammable liquid pool fires and high pressure jet fires with very small amounts of water, there is a need to develop engineering criteria that will allow designers to match a water mist system to a range of fire scenarios and compartment types. This paper draws a parallel between the long-established practices for design of standard sprinkler systems, which allow any experienced designer to custom-fit a sprinkler system to a wide variety of fuels and buildings, and the need for similar principles for the design of water mist systems. Research being carried out by various research agencies has just begun to collect the information required to establish general design criteria for mist systems. The work has concentrated on just a few of the possible fuel types, fuel configurations, and compartment conditions.

Starting with the need to define both the fire hazard and the fire safety objective, the paper presents information on characterizing sprays suitable for water mist systems. The often-asked question "what is the optimum drop size for fire suppression?" is not answered directly, however. Instead it is pointed out that macro-scale effects in large volume compartments cause agglomeration of droplets, so that what starts out as a very fine spray ends up as a much coarser spray. It is also pointed out that the types of nozzles available for producing suitably fine sprays have fairly high pressure demands and, in the case of air-atomizing nozzles, very high compressed-air demands. These factors set a practical limit on the size of compartment that can be protected in a cost-effective way by total flooding systems. An alternative to total-flooding systems for larger compartments would be zoned piping linked with a sophisticated detection system. Much experimental work will be needed to validate such systems.

The matter of determining the spray flux density required for suppression is discussed in depth. It is suggested that methods that average the spray flux density over the entire compartment area or volume, although easy to compute, are quite imprecise when it comes to determining what flux density is required to actually cause extinction. Spray density is likely to vary enormously throughout a compartment as a result of removal of spray on the surfaces of obstructions. It is more efficient to achieve high localized densities in the vicinity of the known fire source by strategic location of nozzles, than to attempt to create a single uniform density in the compartment. More than spray density is required to extinguish flames, however. There must be enough spray energy to interact turbulently with the flame. In this respect, water mist does not act in the same way as gaseous suppressants. A method of measuring actual delivered density in terms of mass of suspended water per volume of air is needed.

Finally, the paper discusses some of the factors relating to ventilation of the compartment, and the effects of spray systems on the pressure conditions in the fire room. The feasibility of discharging a number of air-atomizing nozzles into a closed compartment is questioned. The effects of sudden contraction or expansion of hot gases upon application of the water spray are also discussed.

This paper does not state conclusive design criteria for particular hazards. Instead, it concentrates on the general principles of defining the hazard, deciding on the objective or desired performance of the system, understanding the practical limitations of the equipment, and preparing for the actual interaction of the system with the fire. It is from this basis that the development of design criteria and procedures for a wide variety of hazards must start. Design criteria for particular hazards will have to be built, case by case, application by application, as they were for standard sprinkler systems. With the strong demand to build a data base for efficient design quickly, however, there is a need to combine the efforts of all agencies working on the problem.

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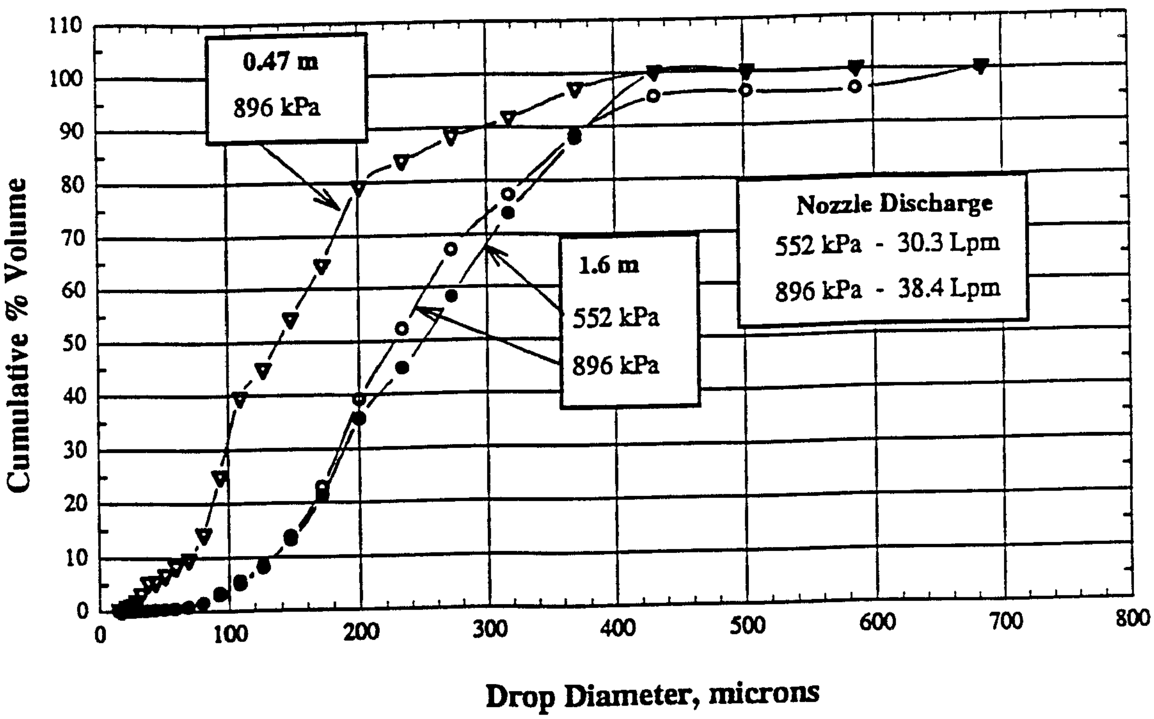
APPENDIX A

List of Figures



3/4 7G-5 at 552 and 896 kPa, 0.47 and 1.6 m from nozzle.

Figure 1. Drop size percent cumulative volume distribution curves for a pressure-type nozzle, at different distances from the nozzle and different operating pressures.

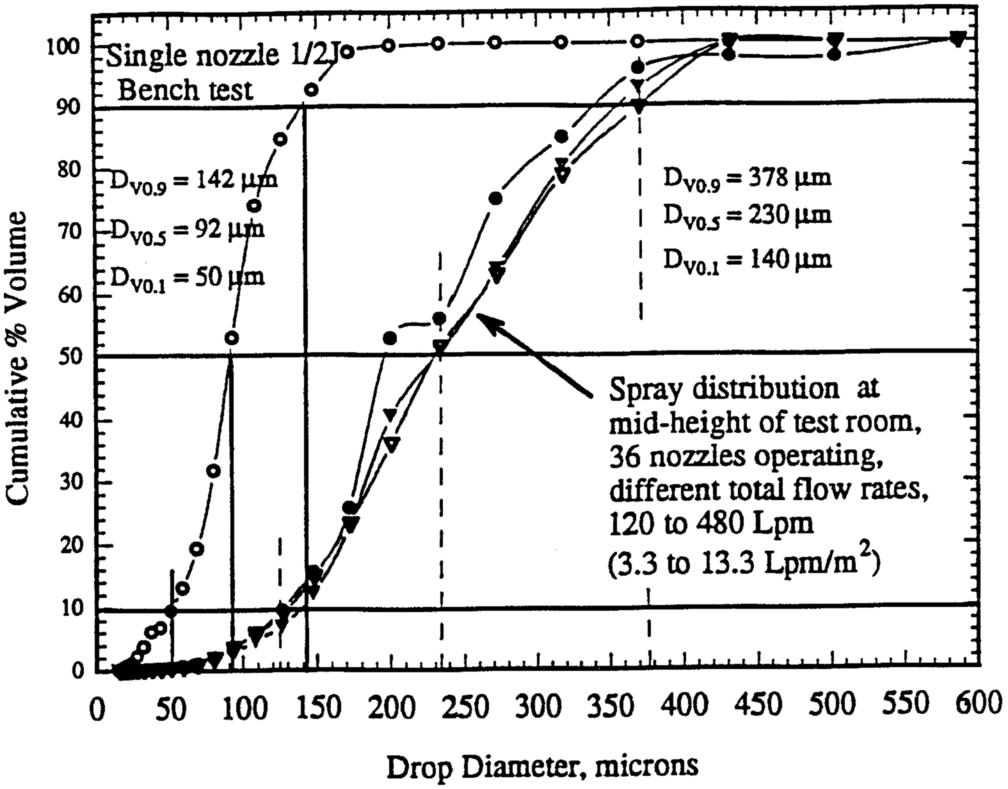


Figure 2. Spray distribution curves for a single air-atomizing nozzle measured 0.47 m from the tip (bench test), and for multiple ceiling-mounted nozzles measured at mid-height in 6 m x 6 m x 3.6 m high test room.

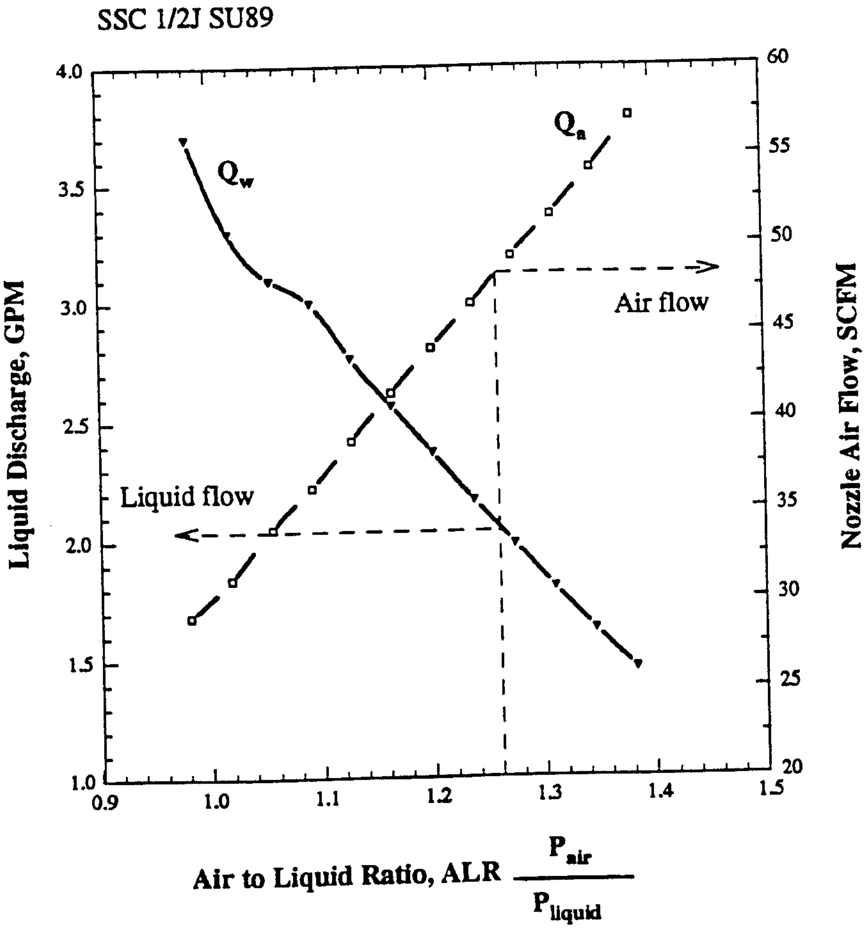


Figure 3. Example of nozzle air and liquid discharge versus air-to liquid pressure ratios (ALR) for air atomizing nozzles.

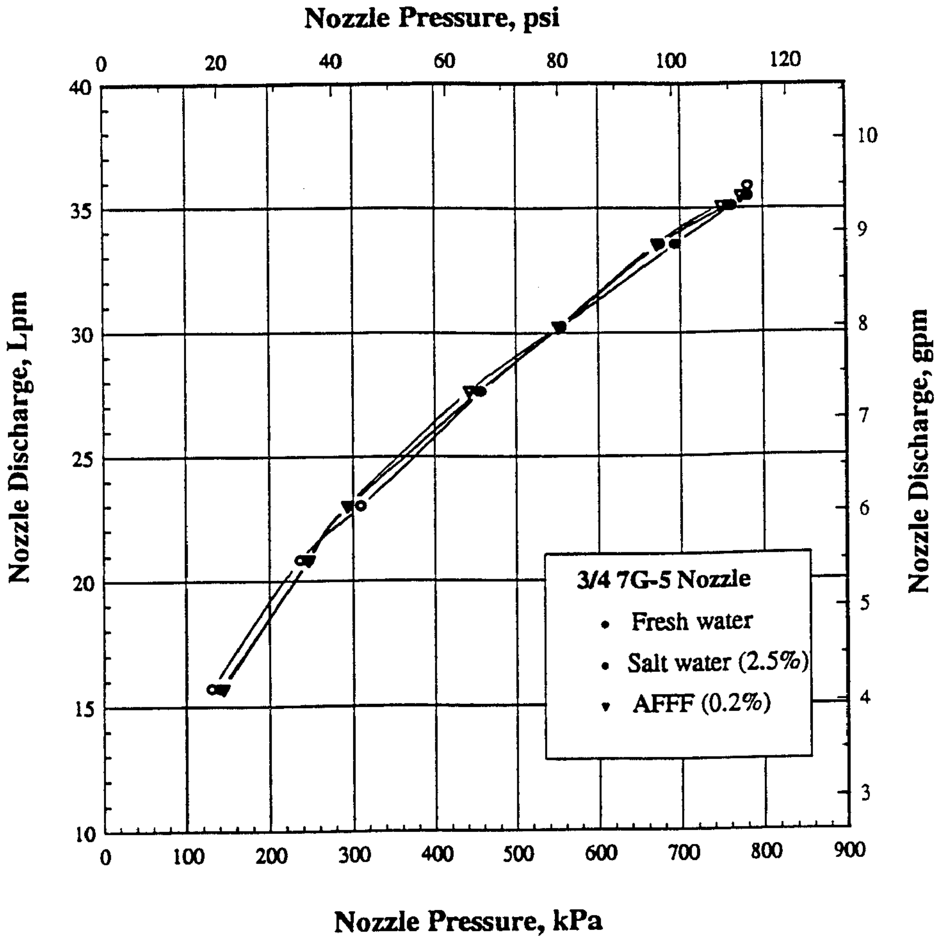


Figure 4. The effect of additives on nozzle discharge characteristics.

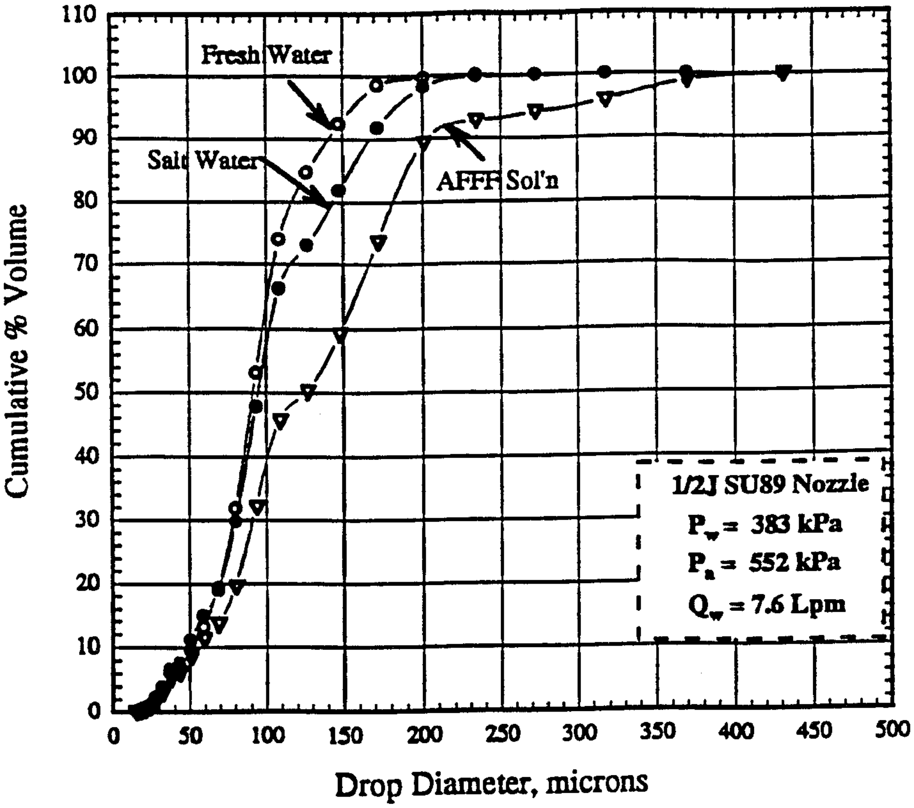


Figure 5. The effect of additives on the drop size distribution of an air atomizing nozzle.

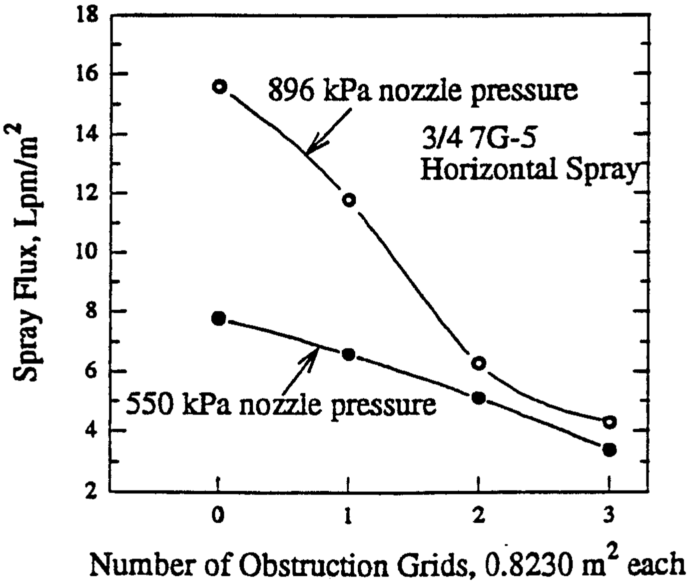


Figure 6. The effect of obstructions on spray flux density.

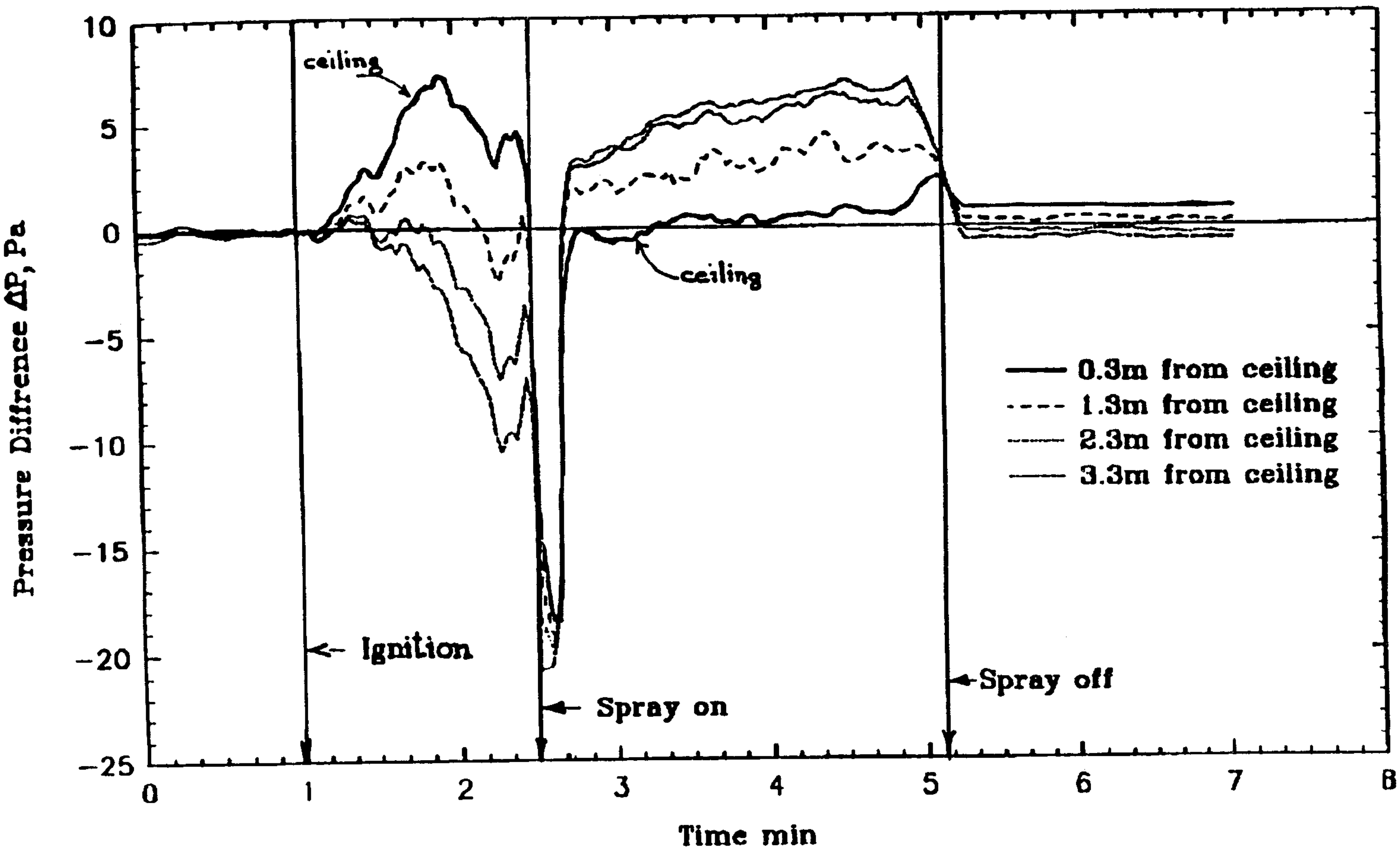


Figure 7. Pressure differences between the fire compartment and adjacent spaces, at four elevations in the room.