

PROTECTING AGAINST VAPOR EXPLOSIONS WITH WATER MIST

J. R. Mawhinney and R. Darwin
Hughes Associates, Inc.

INTRODUCTION

This paper examines a number of practical questions about the possibility of using water mist to mitigate explosion hazards in some industrial applications. Water mist systems have been installed to replace Halon 1301 in gas compressor modules on Alaska's North Slope oil fields. The hazard in the compressor modules includes fire in lubrication oil lines for the gas turbines that drive the compressors. The hazard also involves the potential for a methane gas leak, ignition, and explosion, although the probabilities of occurrence for the explosion hazard are not the same as the lube oil fire. The performance objective for the original halon systems was to inert the compartment, thus addressing both fire and explosion concerns. The design concentrations for the compressor modules were closer to 15% than to 5%, indicating they were intended to provide an inerting effect. As part of the global move to eliminate ozone-depleting fire suppression agents, companies are replacing Halon 1301 systems with water mist systems. The water mist systems were developed and tested for control of liquid fuel or lubricating oil spray or pool fires associated with the turbines that drive the gas compressors. The water mist systems address the most likely hazard, the lube oil fire, but the inerting benefit provided by Halon 1301 has been lost. This has left the question of what to do if there is a methane gas leak unanswered. The question has been asked by the operators of these modules as to whether water mist can provide any benefit for mitigating the gas-air explosion hazard.

There are other industrial applications that involve the potential for gas-air deflagrations where water spray has been considered as a possible mitigating agent. Deluge systems are used in pump rooms on offshore oil platforms as a safety measure. British Gas and other agencies involved in North Sea oil industry safety have studied the effect of deluge water sprays on explosion hazards in these pump rooms. This paper will review some of that work.

Development work on water mist over the past decade has confirmed that it is suitable for extinguishment of Class B (liquid fuel) fires. Prior to the emergence of water mist systems, gaseous suppression agents were typically used for Class B fires, because water sprays from standard sprinklers, or badly managed hose streams, could agitate the fuel surface and intensify burning. The extinguishment mechanisms of water mist of flame cooling, cooling the fuel below its vaporization temperature, radiation attenuation, vapor dilution and extinguishment through oxygen displacement have been reported [1]. A hazard still exists, however, for low flashpoint flammable liquids after extinguishment.

Gas compressor modules and flammable liquid storage rooms present the possibility of accumulation of flammable vapors in a closed compartment. Since water mist systems are being installed in these applications, the question arises as to what benefits can water mist have for addressing gas-air explosion hazards in these settings?

REVIEW OF RELATED RESEARCH

To answer the question "can water mist be used to mitigate explosion hazards?" requires an examination of the experimental work done over the last three decades. That body of work

contains some inconsistencies, but in general it tends to support the idea that benefits of using water mist are substantial, provided attention is paid to the details of application. Jones and Thomas [2], for example, report that it is “never immediately obvious whether application of a water spray will quell or invigorate an explosion.” All of the research seems to confirm, however, that mitigating effects are significant under the right conditions.

(1) Sapko, Furno, and Williams, 1977 [3]

The Bureau of Mines conducted tests to evaluate the ability of water spray to combat methane explosions in coal mines. Both “inerting” and “spray quenching” were studied. Inerting tests were based on the assumption that approximately 26 vol% of water vapor would be required to render a stoichiometric methane-air mixture inert. Inertion-testing showed that droplets less than 10 microns in diameter behaved the same as water vapor. The water requirements for quenching vertical propagations were much greater than inerting concentrations, though it appeared that results were less sensitive to drop size. Flame quenching for a 9% methane-air mixture was successful at droplet water concentrations of 35 mg/cm³. There is a discussion in this paper on the effect of increased spray temperature. At 54 °C the spray produced a higher concentration of water vapor, and reduced the mass concentration required to achieve quenching of a 9.1% methane air mixture. The performance was less dependent on drop size than cooler sprays. This is relevant to the use of superheated water for explosion quenching, and it appears that hot sprays are likely to be more effective than cold sprays.

(2) Acton, Sutton, and Wickens, 1990 [4]

Experiments were carried out to investigate the ability of water sprays to limit flame speed and overpressures produced in gas cloud explosions. Water spray was turned on 1 min prior to the arrival of the flame front, which was passed through an open array of pipework obstacles. Both natural gas and propane were studied. Flame speeds were reduced from 500 m/sec to less than 100m/sec. Overpressures were reduced by an order of magnitude. The authors refer to the expansion ratio of the combustion process (the density ratio of burnt to unburnt gas), and the rate of production of burnt gas (i.e., the reaction rate at the flame front). They conclude that any reduction in explosion overpressures resulting from the use of water sprays must be through their effect on one or both of these factors.

The experimental work utilized deluge nozzles commonly used on offshore oil platforms for pump modules. Droplet sizes in some tests were reported to be in the 800–1000 micron range, although it is not stated what representative drop size this represents. (Such sprays would barely qualify as ‘water mist’ by the definition in NFPA 750, which requires 99% of the volume of the spray to be in drop sizes less than 1000micron.) The authors theorized that the initial overpressure and rapid burning sheared the droplets, greatly reducing the effective mean particle size. It is suggested that, in the absence of particle shearing, droplets should have a Sauter mean diameter of under 100microns, though an optimum size was not offered. An important finding in this study was that larger drops have a mitigating effect only *if they are accelerated*. Thus for unconfined explosions, larger drops may be desirable, whereas for confined explosions, a sufficient volume fraction of very fine drops is needed. The report stresses that the severity of gas cloud explosions is greatly intensified by obstacles and clutter.

(3) Jones and Thomas, 1993 [2]

In this paper the authors reviewed and commented on a total of 38 published reports on the performance of water sprays and mists for suppressing flammable liquid pool fires, dust explosions, hydrocarbon mist explosions and vapor/gas explosions. About a third of the reviewed articles were relevant to vapor or gas ignition scenarios. The authors cited four references where the presence of water droplets actually increased the intensity of a deflagration reaction. In each case, one or more of the following was observed: (1) increased flame speed; (2) faster rate of pressure rise, and (3) higher peak overpressure. This was attributed to the turbulence created by the water spray as the droplets act as obstacles to the expanding fuel volume and fireball. Surprisingly, two studies were referenced where the results tend to indicate that water sprays may be more effective against detonations than against deflagrations. The authors theorize that, unlike a deflagration, a high-speed detonation is able to fragment or “strip” the water droplets into “micromist of exceedingly small size,” which immediately vaporizes and extracts heat energy from the reaction. The authors did not discuss threshold water drop sizes for effective control of deflagrations (though Zalosh [7], claims that water drop sizes for deflagrations should be no larger than 1 micron). Included in the conclusion section of the report are the following verbatim statements:

- Water sprays can act positively against explosions by air-entrainment and evaporation giving rise to mixture dilution and a cooling of hot chemical species.
- Sprays can also act in a negative way by promoting the rapid mixing of fuel and air, by generating turbulence to invigorate the reaction.

(4) Butz, French, and Plooster, 1993 [5]

Butz et al., investigated the use of water sprays to reduce explosion overpressures from 6% hydrogen gas released in a simulated battery room. The test scenario involved creating a stoichiometric mixture of hydrogen and air in a closed chamber, injecting a water spray from an air-atomizing nozzle, then igniting the mixture. The tests demonstrated that ignition would occur in the mist, but required a higher ignition energy than without the mist, and that the overpressure generated by the deflagration was reduced by about 15% (Figure 1). The mist concentration required for successful quench (no discernible pressure rise) was found to be 0.7 l/m³. The water mist system in the test chamber was turned on prior to hydrogen ignition. During a baseline test without mist flowing, peak pressure reached over 35 psia. Exact drop size distribution was not stated, but the Sauter mean diameter was implied to be “smaller than 50 microns.” Figure 1 shows a pressure reduction from 35 to 30 psia “with mist.” Butz also measured a significant temperature reduction of the passing flame front (Figure 2). Such a reduction could reduce the risk of burn injury to personnel who might be exposed to the flash inside the compartment.

Butz concluded that although water mist could not inert the compartment, its use as an explosion hazard mitigant in Navy battery rooms could be justified. Cooling in the compartment reduced the likelihood of an ignition source persisting, and the water mist appeared to increase the energy required for ignition. The design concept would be to turn on the water mist system prior to

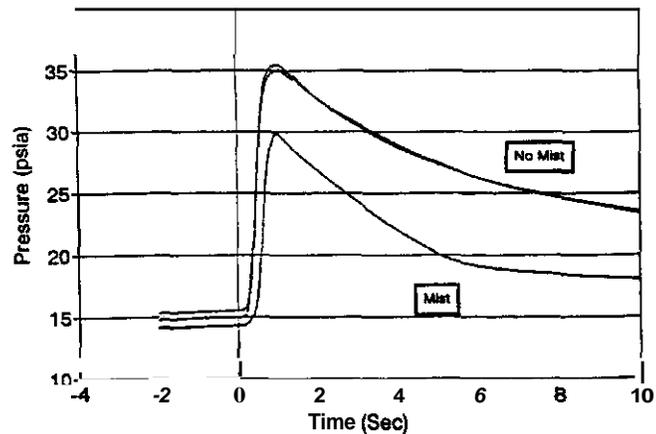


Figure 1. Reduction in explosion chamber over pressure due to presence of water mist [5].

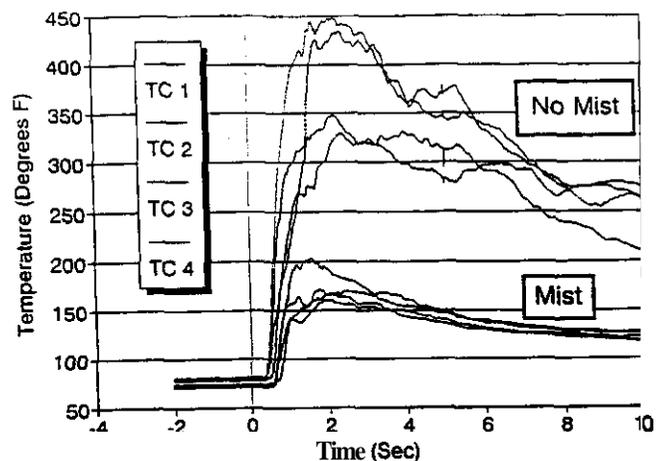


Figure 2. Thermocouple readings of the temperature of the passing flame front, with mist and without mist [5].

ignition, based on gas detection greater than some percentage of the lower explosive limit for the gas/air mixture.

(5) Catlin et al, 1993 161

This paper reports on the influence of water sprays on gas explosions associated with accidents aboard offshore modules. Tests were run with two configurations of the test chamber: (1) closed on all sides with only a single small vent, and (2) one wall entirely open. In the open configuration, the water spray substantially reduced the overpressure. In the confined geometry, the water spray always increased the overpressure resulting from the gas deflagration. Additionally, the presence of water spray in the closed configuration shortened the time to reach the pressure peak. Sauter mean droplet diameters were reported to be 600- 800 microns. (This spray would likely not qualify as “water mist” by the NFPA 750 definition ($D_v0.99 < 1000$ microns)). Turbulence created by the water sprays was attributed to be the cause of the pressure increase for **gas** explosions in the closed configuration. When AFFF was added to the spray, peak overpressures were

reduced. The authors claimed that the reduced water solution surface tension created by the AFFF, facilitated droplet break-up, which reduced the burning rate of the flame front.

(6) Zalosh, 1994 [7]

In 1994, Professor Robert Zalosh of Worcester Polytechnic Institute (WPI) in Massachusetts, prepared for the benefit of the NFPA 750 Water Mist Committee, a summary of a number of studies on the use of water mist to inert/dilute gas-air deflagrations and to reduce flame speeds and associated pressures. The author offered several relevant conclusions based on his expertise and his review of references contained in a bibliography attached to his paper. Significant points are summarized as follows:

- In an unconfined environment, the use of a high momentum water spray can entrain air into the gas cloud and dilute it below the lower flammable limit.
- Water vapor can slightly narrow the flammability limits for a gas; it can dilute the gas/air mixture below the flammability limit. At higher temperatures, higher concentrations of water vapor are possible than at lower temperatures, so warm mist is likely to be more effective than cool mist.
- In near-limit gas-air mixtures, the spray/mist can have either a mitigating effect or an exacerbating effect on flame speeds and pressures depending on the turbulence produced by the spray and the characteristic drop size. The mitigating effect has only occurred with gas concentrations only slightly above the lower flammable limit.
- In the case of a very high flame speed with an accompanying shock wave, the spray/mist can reduce deflagration pressures and possibly extinguish the flame because the shock wave breaks up the drops into a micromist with a characteristic drop size on the order of 1 micron. These tiny drops can evaporate in a sufficiently short time interval to absorb a significant fraction of the combustion energy released during the deflagration.
- The exacerbating effect that occurs in some situations is due to the turbulence produced by the water spray causing the flame speed to increase and/or causing a larger fraction of the flammable gas to burn.
- Generally, drops do not vaporize rapidly enough to absorb the combustion energy before the deflagration is complete, unless they are very small, i.e., on the order of 1 micron.
- More widespread use of water spray systems for deflagration control will depend on the viability of generating a micromist with sufficiently small drop sizes. This will require water mist systems that are different from those being developed commercially for fire suppression applications.

(7) Johnson and Shale, 1995 [8]

This paper provides a summary of research performed by British Gas Plc on the mitigation of explosions on offshore oil and gas platforms. Conclusions presented relative to water spray/mist performance are consistent with the above summaries. British Gas sponsored considerable research in this area following the Piper Alpha disaster in 1988, in which a gas explosion on an offshore platform resulted in total destruction of the platform and the loss of 167 lives. The paper emphasizes how interior clutter and obstacles within a space can considerably increase flame speed and peak overpressure. The paper warns of the possibility that water spray can make matters worse (quicker pressure rise, higher peak pressure, faster flame propagation), especially for droplets “around 150 microns.” No recommended drop size is presented, though the authors refer to Sapko et al. 1977 [3] above, which focused on drop sizes of about 10 microns. The

authors discuss the possibility of small droplet generation by droplet break-up in gas ignition scenarios resulting in “high flame speeds.”

(8) Selby and Burgan [9]

Much of the work done in the 1990s on explosion hazards on offshore platforms was conducted at the British Gas (BG) Spadeadam facility in northern UK, as part of a multi-year, multi-industry study aimed at improving the oil industry’s confidence in its safety systems with respect to hydrocarbon fires and explosions. In addition, the project had an information exchange agreement with the Christian Michelsen Research (CMR) organization in Norway. This enabled experimental data and project information to be exchanged between BG’s project and CMR’s Gas Safety Programme. The final report on this multi-year project contains experimental results and conclusions from the study. Relevant project findings are summarized as follows:

- Researchers investigated “clutter,” equipment at several equipment densities, plus different wall perimeter confinement, using two types of water deluge system, varied fuel concentration and ignition location. Test results confirm that obstructions and clutter must be considered in explosion hazard assessment. Overpressures increased when the equipment density increased, and factors such as whether ignition was at the end or in the center of the test rig, affected overpressure. The high equipment density configuration increased the potential for flame acceleration.
- Unconfined (one wall open) conditions demonstrated greater reduction in overpressures than enclosed conditions. Figures 3 and 4 illustrate the difference in overpressure between unconfined and confined conditions. Figure 4 also shows that the rise to peak overpressure occurred significantly sooner with the mist on than with no mist.
- Larger drops must experience an acceleration and shattering into very small particles for the mitigating effect to be realized. This acceleration occurs with an unconfined compartment, but less so with a completely closed compartment.
- Two proprietary nozzles, both commonly used in offshore deluge system, were used in these tests. The deluge rates for these two nozzle types were chosen such that they would generate the same water volume fraction (the same quantity of water in a given volume). Deluge rates for the two water spray systems were 17 l/min/m² for the MV57 nozzles and 35 l/min/m² for the LDNs averaged over the floor area of the test rig. (Both nozzles generate sprays that would not qualify as water mist by the definition in NFPA 750.)
- The large drop nozzles resulted in lower overpressures than the other nozzles. (This indicates that either larger drops were more effective at reduction than smaller drops, OR that the assumptions about both systems having the same water volume fraction were wrong, and instead the increased mass discharge rate was the reason for the different performance.)
- The results confirm earlier work by British Gas of how water deluge influences gas explosions. To be effective, relatively high gas velocities are required in order to break up the water droplets in the water spray into much smaller drops. These smaller drops, which present a much higher overall surface area, are able to extract energy from and inhibit combustion in the explosion flame.

DISCUSSION

The research reviewed provides qualified support for the argument that there are potential benefits to injecting water mist to mitigate explosion hazards in a compartment. These benefits include cooling of potential ignition sources; increase in ignition energy required to ignite a fuel-air

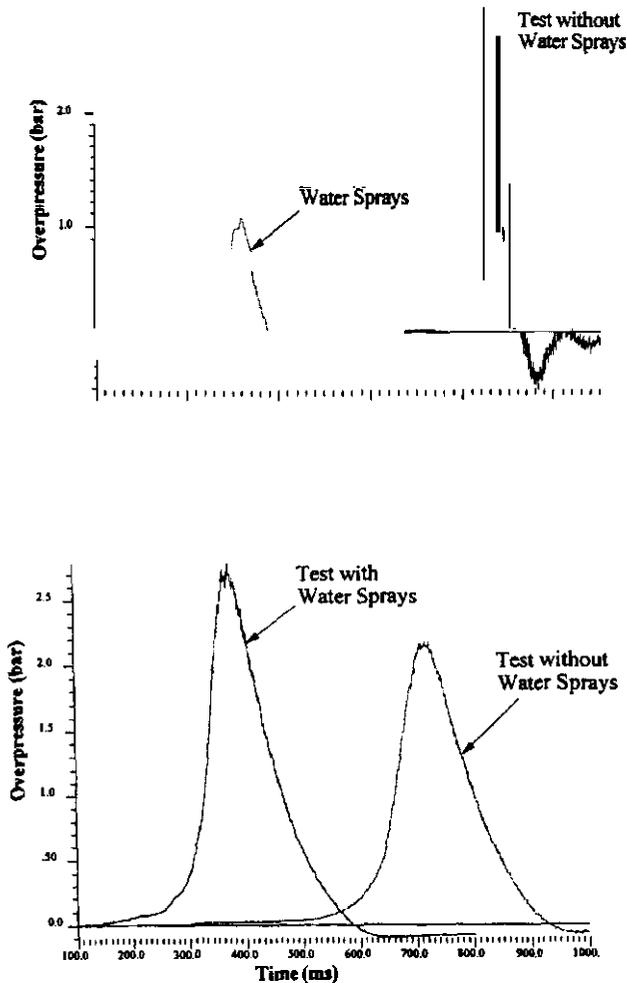


Figure 4. Blast overpressures measured in an enclosure with no open side, with and without water mist [9].

All of the researchers highlighted the fact that for pre-mixed vapor-air mixtures an explosion may be exacerbated by injection of water mist, as clearly shown in Figure 4. The experimental work is not always consistent, however. In Butz's study [5], a small overpressure reduction was achieved in a completely closed container with a pre-ignition mist concentration. This is contrary to the British Gas finding [8,9] in which the water mist was ineffective at reducing overpressure in a closed compartment. It is likely that the drop size distributions of the nozzles used were radically different—the Butz twin-fluid nozzle qualifying as a water mist ($D_{v0.90} = 300$ microns), whereas the oil platform deluge nozzles produced a much coarser spray.

The following factors appear to be particularly important in determining the outcome of an ignition event:

- Drop sizes must be small enough to evaporate within the short time frame event of a fast moving flame front: “normal” water mists may not create a high enough fraction of very small drop sizes.
- Larger droplets provide a benefit for energy stripping, i.e., absorbing energy from a pressure wave: therefore, an effective water mist must have a range of drop sizes, from sub 50 micron to 600 to 800 microns.
- Larger drops must be accelerated for energy stripping to occur, i.e., an avenue for movement is needed: a completely closed compartment charged with water mist does not permit such movement.
- The turbulent mixing of the vapor-air mixture increases the surface area of the flame front, hence the burning rate and velocity.

The experimental work reviewed above identifies three elements that warrant further attention:

1. The role of the drop size distribution needs to be better understood and better controlled in the experimental work.
2. The importance of allowing a degree of movement of the water particles needs to be better understood. For example, should the compartment be partially open (vented), rather than closed, as is required for fire extinguishment?
3. The need to have the water mist pre-established in a compartment before ignition, rather than attempt to inject the mist after ignition has been detected needs further investigation. For relatively small uncluttered compartments, it may be acceptable to wait for the ignition before injecting the spray. In larger machinery spaces, mist with appropriate qualities must be initiated before ignition. It would be comforting to know where the dividing line lies.

The water sprays used in most of the British Gas experimental work were coarse sprays when compared to water mist, as defined by NFPA 750 [10]. Although, on the one hand, large drops are “good” in that they absorb pressure energy through energy stripping, it is also of great importance to extract the heat from the flame front by evaporating the smallest droplets. As remarked by Zalosh [7], to quench a flame front in a fuel air mixture requires water droplets “orders of magnitude finer” than occurred in any of the experimental work. Selby and Burgan [9] also conclude that the variability in results of explosion mitigation testing is probably due to insufficient control over drop size in the various experiments.

Evidence that water mist with sufficiently small drop sizes may quell a dust explosion is found in work conducted at the Irish agricultural research facility involving dusts of dried milk products. A dust explosion mitigation system has been developed for milk solids dryers in the Irish dairy industry. In unconfined tests the rapid deluge of the fine mist after ignition of a 1-kg dust packet quelled the dust cloud deflagration. The Irish agricultural research agency conducted additional tests in moderate size enclosures, with similar positive results. The mist generating method involves the “flashing” of superheated water released from a self-pressurized container [11]. Water is superheated to 175 °C in containers up to 70 liters in volume. This puts the cylinder at a pressure of approximately 10 bar (145-psig). When released to atmospheric pressure, about 12 to 14% of the water flashes directly to vapor phase, then condenses into aerosol-size particles

(< 20 microns) as the cloud cools. There is a dynamic release of energy as the liquid flashes, which shatters the remainder of the mass of water into relatively fine spray ($Dv_{0.90}$ – 300 microns [Figure 5]), and results in a rapid distribution of “mist plus fog” throughout the protected space. About 14% of the mass of water discharged flashes to vapor, then immediately re-condenses. The condensed ‘fog’ is “an order of magnitude” finer than can be achieved by mechanical generation of spray. Figure 5 compares a cumulative percent volume drop size distribution plot for a mechanical nozzle and a ‘flashed’ spray [11, 12]. The flashed spray shows more than 30% of the spray mass in sub-50 micron drop sizes, whereas the “standard” water mist nozzle has less than 5% of its volume in sub-50 micron sizes. The mitigating effects of the super-heated water mist on dust explosion may be due to the high mass fraction in very small drop sizes.

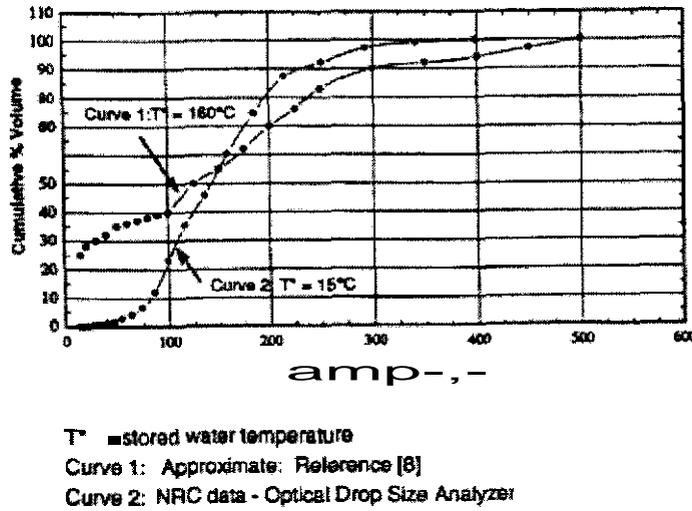


Figure 5. A cumulative percent volume drop size distribution plot for a mechanical nozzle and a ‘flashed’ spray. The flashed spray shows more than 35 vol% in the sub-50 micron range.

APPLICATION OF RESEARCH FINDINGS

Having reviewed the experimental work, we can now return to the question of whether water mist installed for fire suppression purpose can be used in any way to mitigate the potential explosion hazard in the North Slope gas compressor modules. The following observations are offered for consideration:

Drop size distribution. The water spray characteristics that “passed” the Factory Mutual test protocol for gas turbine enclosures and machinery spaces were suitable for a Class B liquid fire application. Nozzles produced by different manufacturers differ greatly in drop size distribution, so it is not possible to make general statements about how water mist will perform. With the exception of the superheated water system proven successful for dust explosion hazards, water mist manufacturers’ sprays may not have a high enough fine fraction to reduce the overpressure caused by a deflagration in a fuel/air mixture. Without specific fire/deflagration testing, it is not possible to say at this time.

Emergency ventilation. Should ventilation be shut off on activation of the water mist system, as required for liquid fuel fires, or, should ventilation be increased, as required for explosion

hazard management when there is a flammable gas leak? The fire extinguishment requirement is contrary to the best practice for explosion hazard management. The explosion prevention measures should have precedence over the fire extinguishment measure. If a methane gas *leak* is detected, with no fire, emergency ventilation should be started and maintained.

Emergency venting. Compartments where an explosive mixture of gases could occur should be equipped with blowout panels or explosion relief panels, even when it is planned to activate the water mist system to mitigate the hazard. The experimental work shows that the magnitude of a deflagration overpressure may be reduced, but it cannot be eliminated with certainty. The research suggests that the mitigating effect of water mist (on overpressure) requires a degree of openness to the compartment to accelerate the larger droplets. Therefore, relief panels would provide a double advantage.

Pre-emptive activation. On the first indication of a methane gas leak, pre-emptive application of the water mist system is likely to provide better protection than waiting to activate the system in response to an incipient deflagration. At least the potential benefits of cooling ignition sources, and protecting personnel against exposure to the flash flame front are relatively certain. The extent of venting of a “fireball” from a deflagration is also likely to be reduced by the presence of water mist.

Post-ignition activation. Except in small and uncluttered spaces, it appears unreliable to presume to **quell** a fuel-air explosion after it has begun. For anything other than small distances, spray delivery problems (e.g., spray velocity, travel distance, obstructions, uniformity, turbulence) complicate performance. Increased turbulence in the flame front may increase overpressure and accelerate the burning rate. Therefore, a water mist system should be activated prior to ignition, based on gas sensor readings indicating an increasing vapor/air concentration approaching the LEL.

Explicit design. A water mist system intended for explosion hazard mitigation must be expressly designed for that purpose. Many of the features of the water mist system will have been designed for the Class B fuel scenario. Some of those features will have to be revised or overridden to deal with the explosion hazard. For example, some water mist systems incorporate “cycling,” i.e., on-off intervals of the nozzles. Cycling would be undesirable in an explosion hazard mode.

Fire testing. NFPA 750 is explicit about the need for fire testing to establish the design criteria for water mist systems for fire/suppression /extinguishing systems. This need to conduct at least a few tests is equally as important for explosion suppression systems. A test protocol for evaluating pre-emptive systems is required. A completely different test protocol would be required for a system intended for post-ignition quenching.

CONCLUSION

A review of the relevant literature on deflagrations and water mist reveals that a water mist system designed for explosion hazard mitigation would differ in important ways from what is required for the Class B liquid fuel hazard. A combined explosion hazard/fire hazard water mist system must be expressly designed for both hazards. This is not easy to do since the required performance objectives may be contrary. Basic decisions about which objectives have the highest priority must **be** made.

The research indicates that there is a high probability that a water mist system will mitigate explosion pressures, but that some aspects of the design are unpredictable. It is proposed that improved control over drop-size distribution, mist density, and the details of application (spray velocity, nozzle spacing, activation timing, and ventilation) are crucial to realizing benefits and minimizing negative effects. As is required for all water mist systems, a test protocol should be prepared to determine the proper design parameters. Existing water mist systems may be adapted to provide explosion hazard mitigation. However, changes in the operational features of a water mist system designed for liquid fuel fires must be made in order to make the system suitable for fuel-air explosion hazard mitigation. This paper outlines the type of operational features that are needed. It recommends that a test protocol be developed to verify the performance of water mist in protecting against vapor explosions.

REFERENCES

1. Mawhinney, J.R., B.Z. Dlugogorski, et al., *A Closer Look at the Extinguishing Properties of Water Mist*, International Association for Fire Safety Science (IAFSS), Ottawa, Ontario, Canada, 1994.
2. Jones, A., and Thomas, G.O., "The Action of Water Sprays on Fires and Explosions," *Process Safety Environment*, Institution of Chemical Engineers, Vol. 71, No. 1, 41-49, 1993.
3. Sapko, M.J., Furno, A.L., and Kuchta, J.M., *Quenching Methane-Air Ignitions With Water Sprays*, Report of Investigations 82 14. Bureau of Mines, US Department of the Interior, 1977.
4. Acton, M.R., Sutton, P., and Wickens, M.J., "An Investigation of the Mitigation of Gas Cloud Explosions by Water Sprays," British Gas MRS E 595, Presented at Piper Alpha: Lessons for Life Cycle Safety Management Symposium, Institution of Chemical Engineers, London, 26-27 September 1990. (Copy on file with the author.)
5. Butz, J.R., French, P., and Plooster, M., "Application of Fine Water Mists to Hydrogen Deflagrations," *Proceedings*, Halon Options Technical Working Conference, Albuquerque, NM, pp. 345-355, 1993.
6. Catlin, C.A., Gregory, C.A., Johnson, D.M., and Walker, D.G., "Explosion Mitigation in Offshore Modules by General Area Deluge," *Trans IChemE*, Vol. 71, Part B, pp. 101-111, May 1993.
7. Zalosh, R.G., "Water Mist for Deflagration Control." Summary Paper Prepared for the NFPA Committee on Water Mist Suppression Systems, March 27, 1994. (Copy on file with the author.)
8. Johnson, D.M., and Shale, G.A., "Research on the Mitigation of Explosions on Offshore Oil and Gas Platforms," British Gas Plc., Research and Technology Division, UK, circa 1994. (See Selby and Burgan [9].)
9. Selby, C.A., and Burgan, B.A. (eds.), *Joint Industry Project on Blast and Fire Engineering for Topsides Structures, Phase 2; Final Summary Report*, Ascot, Berkshire, The Steel Construction Institute, UK, 1998.
10. National Fire Protection Association, "NFPA 750, Standard on Water Mist Fire Protection Systems," National Fire Protection Association, Quincy, MA, January 2000.

11. Mawhinney, J.R., Taber, B., and **Su, J.Z.**, "The Fire Extinguishing Capability of Mists Generated by Flashing of Super-Heated Water," Presented at: American Institute of Chemical Engineers, 1995 Summer National Meeting, Boston, MA, 1995. Copy on file with the author.
12. Keary, J., and McGovern, R., *Charuacterisation of a Heated Water Extinguishing System: Report prepared for M. O'Connell*, Department of Experimental Physics, University College Galway, Galway, Ireland, May 1994.