Use of Fine Water Mist
for Naval Aircraft Fire Protection and Explosion Suppression

by
Joseph E. Wolfe and Paul DeSipio
Naval Air Warfare Center-AD
P.O. Box 5152, Code 6013
Warminster, PA 19874-0591

PROGRAM OBJECTIVE

For Naval Aircraft the Fine Water Mist system must provide adequate mist concentration as rapidly as possible with enough small droplets having a sufficient momentum to penetrate the flame and surround obstructions.

INTRODUCTION

This paper reports the results of analysis and testing conducted at the Naval Air Warfare Center Aircraft Division Warminster, PA. Fine Water Mist systems are being investigated for fire protection of engine nacelles and explosion suppression in the dry bays and fuel tanks of Naval Aircraft. The Navy is studying Fine Water Mist as an alternative to Halon 1301 and 1211. Fine Water Mist has no ozone depletion or global warming potential and no toxicity problems. Several aircraft applications differentiate this study from other work involving Fine Water Mist. On board aircraft systems have significant weight restrictions requiring a minimum amount of water stored and a maximum system efficiency. For engine nacelle fire protection systems, the engine compartment size, air flow through the nacelle and obstructions in the nacelle affect the extinguishment process. Additionally, the type of fire (pool fire or spray fire) and the type of fuel (aviation fuel or hydraulic fluid) influence the extinguishment process. The critical factor for dry bays and fuel tank explosion suppression is the system actuation response time. A Stoichiometric mixture of JP-4 and air has an approximate flame speed of 9 ft/s and a burn velocity of 2 ft/s at standard conditions. The associated pressure wave expands with the flame front and will cause a deflagration. In a small compartment this pressure build-up is rapid (approximately 40 milliseconds) and the Fine Water Mist system must activate quickly to reduce the pressure build-up and interact with the flame front to prevent an explosion.

BACKGROUND

The Montreal Protocol of 1987 identified a number of Halons as contributors to the depletion of the Earth's ozone layer. As a result there are several programs worldwide searching for a replacement agent or alternative to Halon. Recently a great deal of research has been conducted in the development of Fine Water Mist systems as an alternative to Halon extinguishment systems. The fine mists are effective because they expose a very large surface area of water to the heat source or flame. Additionally, water has a high heat capacity and a high latent heat of vaporization which are favorable physical properties for fire suppression. The water is characterized as a mist when 90% of the volume (Dv90) of drop sizes are less than 400 µm in diameter. For drop sizes larger than 400 µm the water is defined as a spray (Mawhinney). In normal circumstances the mechanisms of fire extinguishment with Fine Water Mist are air/gas cooling, cooling of hot surfaces, rapid steam expansion, oxygen depletion and smothering of the flame.

The Navy is evaluating fighter/attack aircraft as the primary aircraft for fire protection and explosion suppression. The aircraft's engine fire extinguishing system is designed to provide protection for the APU, AMAD and engine bays. There are three separate distribution lines for the fire extinguishing system. There is one distribution line for the APU bay and one distribution line for both the right and left engine/AMAD bays. The larger engine and AMAD bay volumes govern the system design. Currently there is no design for an active explosion suppression system on board any Naval Aircraft. Dry bays and fuel tanks are the two areas such a system might be employed. A dry bay is a compartment or an internal volume, inaccessible during flight, subject to combustible fluid leakage due to combat damage or equipment failure. The total dry bay volume is approximately 16 ft^3. It is estimated that the center dry bay region is 50% full of equipment and the outer region is 25% full.

Fuel tank ullage is the amount of space, or volume, that is absent of fuel in a fuel tank, in other words the air/fuel vapor volume. This volume increases as fuel is consumed or drained. The vent tanks are also an area of concern as they are always full of air and fuel vapor. Class B Flammable liquid fires are the main threat in the engine nacelle. There are three general types of flammable liquid fires: (1) fires in liquids of appreciable depth, deeper than 1/4 inch, (2) spill or running fires in liquids of no real depth, less than 1/4 inch, and (3) pressurized liquid or gas fires (Cote). Engine nacelles are heavily cluttered and any neighboring obstruction can act as a flame holder increasing the stability of the fire.

FLAME PROPAGATION

The ingredients necessary for combustion are fuel vapor, air and an ignition source. The air may be at ambient atmosphere surrounding the aircraft, in the case of fuel external to its confinement, in the vent space above the fuel in the tank due to the normal breathing of the system, or evolved from the fuel with fuel vapor in a climb to altitude. The heat to vaporize the fuel may come from hot engine parts, ambient temperatures, equipment within the system such as pump or valves, or aerodynamic heating. The ignition source may be a spark, flame, hot surface or an anti aircraft round.

The ability of flame to propagate throughout a closed region and through small relief openings is known as explosion propagation. Propagating reactions are those in which the reaction initiates at a specific point in the material and propagates from that point as a reaction front through the unreacted material. The term explosion is best defined as a sudden release of pressure or energy. There are two types of explosions for a combustion process, deflagrations and detonations. The most severe type of explosion for a combustion process is a detonation characterized by supersonic propagation rates (where the velocity is greater than 1100 ft/s) relative to the unburned reactant. The more common type of explosion for a combustion process is the deflagration of a flammable mixture, characterized by the subsonic propagation rates (where the velocity is less than 1100 ft/s) relative to the unburned gas. The explosion pressure of a deflagration is greatest in adiabatic combustion under total confinement, i.e., constant volume. Explosion pressures of mixtures less optimum than Stoichiometric are generally lower because of decreased enthalpy and burning velocity, but also because of the restricted mode of flame propagation, i.e., upward, horizontal or downward. If the explosion can be contained and the pressures relieved, usually little or no damage results. For this reason, apparatus that can become a source of ignition, either during normal operation or following a malfunction, are required to be explosion proof if located within zones that may have fuel vapors during the aircraft lifetime. Additionally, there is a possibility that a physical explosion can occur. In a physical explosion no combustion takes place. The potential energy release associated with physical explosions, such as in a boiling liquid-expanding vapor, usually culminates in a large fireball. Liquefied petroleum gases are normally involved in these explosions and result when the fuel container is excessively heated by an external fire and ruptures from overpressurization(Kuchta), (Tunkel).

WEIGHT RESTRICTIONS

The fighter/attack aircraft is being used to model prototype designs because of the weight restrictions imposed. The current Halon 1301 fire extinguishing system design weight is 20.5 pounds. There are concerns about using water mist instead of Halon with respect to weight. First, one gallon of water weighs 8.345 lbs. Although very small amounts of water have been proven effective in 20" diameter pan and spray fire tests, the amount of water required for full coverage in an engine nacelle has yet to be determined. There is a great potential for concentration loss to surfaces and obstructions in highly cluttered areas, and gravity fallout is a concern where the drops must travel a long distance. These factors could increase the amount of water necessary for effective coverage. Full scale engine nacelle testing will determine the amount of water and nozzle location requirements. The exact number of nozzles required will be a large factor in determining overall system weight. Each additional nozzle also requires more plumbing and support weight. Also, if air atomizing nozzles are used additional weight will be required for separate air lines and a possible air storage container (if engine bleed air is determined unsatisfactory). The weight of the fine water mist nozzle will vary with design and depend on the determined final optimum spray conditions. The main factors involved with the weight of the water storage container will be the amount of water needed and the pressure required.

FINE WATER MIST NOZZLES

Two types of nozzles were tested. The first were two types of hydraulic atomizing nozzles, whirl and impingement. These nozzles use only a high pressure liquid feed to produce the spray. Whirl nozzles utilize an internal unit to create a vortex within a cylindrical body to create fine droplets. In an impingement nozzle, atomization results from a laminar liquid jet impinging on a metal pin of equal diameter. Hydraulic pressure nozzles rely on water pressure to force water through one or more small orifices so that jets become unstable resulting from interaction with the surrounding gaseous medium which causes rapidly growing surface waves. Disintegration occurs when the wave amplitude reaches a critical value; fragments of the jet are tom off and rapidly contract into unstable ligaments under the action of surface tension. This process is sometimes referred to as primary atomization. If the drops so formed exceed critical size, they further disintegrate into drops of smaller size, a process known as secondary atomization (Lefebvre).

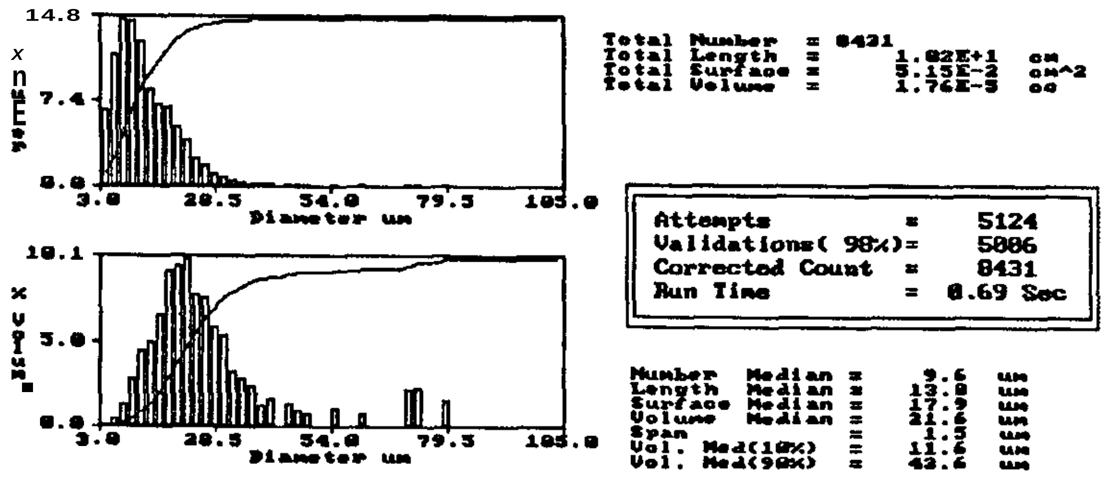
The second type is air fluid atomizing nozzles which use both an air feed and a liquid feed to produce a fine mist. The air and water streams meet in an annular mixing chamber within the nozzle and are dispersed together. The energy in the compressed air is used to atomize the liquid and propel the mist. Given a constant liquid pressure, the liquid flow is reduced as the air pressure is increased. Air consumption will increase, resulting in finer atomization. These produce acceptable water mist properties using low air and water pressures. However, there are two separate lines to install, increasing the cost in large applications. A variety of nozzles and mist patterns have been tested: round and wide angle full cone, a flat fan and air atomized fog patterns.

a) MIST MEASUREMENT PARAMETERS

The NAWC, Warminster spray lab contains a Phase Doppler Particle Analyzer (PDPA) which is used to perform the Fine Water Mist measurements. The PDPA provides accurate measurements of Sauter Mean Diameter (D32), Median Volume Diameter (D30), Number Density and Velocity Mean among other parameters of the mist Drop size refers to the size of the individual droplets which comprise a nozzle's mist pattern. All of the droplets within a given mist are not the same size. Fine Water Mist systems are commonly evaluated based on the droplet *size,* droplet velocity, mist density and quality of the mist using Dv10 and Dv90 measurements including the Sauter Mean Diameter (SMD) among other spray characteristics. The Sauter Mean Diameter is a means of expressing the fineness of a mist and is defined as the diameter of a drop having the same volume to surface area ratio as the total volume of all the drops to the total surface area of all the drops of the mist.

The Air to Liquid ratio (ALR) is an important parameter for air atomizing nozzles. The ALR should be expressed as the ratio of the mass of air flow to the mass of water flow through the nozzle. The ALR changes as the balance between air and water changes. Typical commercial air fluid atomizing nozzles operate with an ALR between 0.1 and 0.3, which means that the mass flow of air is 10 to 30 percent of the mass flow of water. Although it is desirable to have a very low ALR, the mist must have adequate drop size distribution and projection to be effective. These aspects of nozzle performance at ALR's less than 0.1 should be confirmed by testing (Mawhinney).

Research continues in the water mist community to determine if total flooding of water mist will act as a gaseous agent. However, the ability of water mist to act as a gas has yet to be observed. In total flooding applications, an excellent overall mist flux density can be obtained. Mist flux density is defined as the flow rate per unit area (or volume). Unfortunately, the mist momentum will be lost due to very low velocities in total flooding applications. Mist momentum is determined theoretically by multiplying the average mass of air and water per unit volume of mist by the average velocity of that unit volume. Mist momentum is the most practical parameter for extinguishing fires because, if the mist does not have the energy to penetrate the flames and interact with the fire it can not extinguish the fire (Mawhinney). Since most of the nodes tested in our spray laboratory were limited to smaller droplet sues (for faster evaporation rates) the operating parameter becomes the velocity of the mist. Therefore, nozzles that produce the highest velocity and largest number of small droplets in the mist will be the most successful. Although the percentage by volume distribution is used for heat transfer calculations, it is the percentage by number distribution that will inform the designer as to the number of small droplets. It has been seen in laboratory conditions that the volume distribution differs, sometimes, greatly from the number distribution. This is mostly likely caused by the optical instrument recording a few large diameter droplets that are unrepresentative of the **mist.** However, these large droplets will be a major portion of the volume and will affect the volume distribution. For instance in figure -1- , note that the Dn10= **4** µm and the Dn90= 20 µm in the % number vs diameter graph. This is to say that 90% of the number of droplets produced by the nozzle are 20 µm in diameter or less. Now compare that to the Dv10= 11.6µm and the Dv90= **43.6** µm **for** the same mist in the % volume vs diameter graph. This informs the designer that 90 % of the volume of the mist is **43.6** µm in diameter or less. The more accurate means of expressing volume is to use the 90 % of the number of droplets and calculate that as a "working volume". Unfortunately, this is a rather tedious calculation. Figure -2- Velocity vs Diameter graph illustrates the working volume for the same mist. Note the clutter of droplets and the few satellite droplets that surround them. These few droplets, individually, do not add any significant fire extinguishment capability, but they do contribute to the total volume of the mist.



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Total Number   = 8431
Total Length   =        1.02E+1   cm
Total Surface  =        5.15E-2   cm^2
Total Volume   =        1.76E-5   cc

Attempts               =     5124
Validations( 98%)=     5006
Corrected Count    =     8431
Run Time               =   0.69 Sec

Number   Median =      9.6   um
Length   Median =     13.0   um
Surface  Median =     17.9   um
Volume   Median =     21.6   um
Span            =      1.5   um
Vol. Med(10%)   =     11.6   um
Vol. Med(90%)   =     43.6   um
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Figure -1- Accumulated % Medians

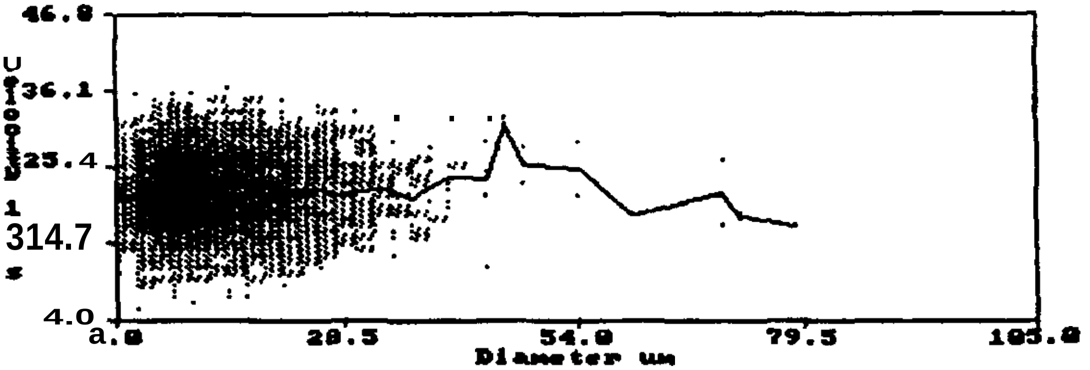

Figure -2- Velocity vs. Diameter graph

Surface tension is defined as the specific free energy of a liquid surface at interface with another fluid. It is of importance in gas evolution and solubility, and has a pronounced affect in atomization. Fluids with large cohesive forces between molecules such as water exhibit high surface tensions. Surface tensions decrease as temperature increases and molecular cohesive forces are overcome. At the fluid's critical temperature, surface tension ceases to exist. The main effects of surface tension are on minimum operating pressure, spray angle and drop size. A lower surface tension increases the spray angle and decreases the drop size usually at lower operating pressures. Increased temperature of water will lower surface tension and will improve spray pattern quality, increase spray angle, decrease droplet sue and increase velocity and momentum. In other words, in theory, an increase in temperature improves atomization. Therefore, the use of a proper additive with the water or an increase in temperature or a combination of both will lower the surface tension and improve atomization.

TESTING AND RESULTS

Many commercially available nozzles have been tested. Using only a small volume of water is very important in this application since the water must be atomized and delivered in a few milliseconds, especially in explosion suppression. The smaller the drop size, the more effective it becomes for fire extinguishing. Heat is transferred to a droplet by radiation, conduction and convection. The heat transfer rate is proportional to the droplet volume and the surface area. The smaller the volume the greater the number of droplets and the greater the surface area exposed. The ideal droplet size for an individual application is one which, when introduced into a flame front, will increase its temperature, absorb full latent heat, boil and completely evaporate. Large droplet diameters are ineffective and will extract little or no heat. With this in mind, testing was conducted on nozzles that had maximum droplet diameters in the 100 µm range. Nozzles that produced droplets of larger diameters had too high a flow for our application. Many of the commercially available nozzles were not practical for our application and these tested nozzles could not extinguish a 20" pan fire (approximately 128 kW) of JP-5. The fine mist had virtually no momentum at high pressures, too low of a water flow or too high of an air flow requirement for an air atomizing nozzle. Also, another factor affecting pan fire extinguishment was pressure of the hydraulic nozzle. Some performed better at lower pressures because the mist continued to expand outward. At the higher pressures the mist from most hydraulic nozzles tested tended to expand outward, then contract for some distance before expanding again. These problems led to the in-house development of several high momentum nozzles. The high momentum nozzles are air atomizing nozzles which are designed to maximize momentum and velocity while minimizing pressures.

a.) TIME RESPONSE TESTING

It has been demonstrated by Bragg in tests conducted with propane air mixtures that an ultra fast dispersion of water mist can suppress explosions. However, he observed that a sustained mist was needed for the energy absorption to exceed the rate of energy release by the deflagration. Additionally, Butz successfully used water mist to quench hydrogen air deflagrations. However, he noted that sufficient time must be available for the mist concentration to reach a level required to assure the quenching of a deflagration. Further, both researchers observed that smaller droplet sizes are more effective for heat transfer. These researchers led to the conclusion that to quench a deflagration, water mist must be dispersed quickly at high velocity; it must contain small droplet sizes, and must be sustained for a certain duration to eliminate a pressure rise. In time response testing conducted at NAWC, it has been demonstrated that a water mist system reacts in 8 msec to produce the first droplet with a full mist present in 125 msec. However, it must be shown that there is enough mist present at the design goal of 40 msec, to quench a ***JP-4*** deflagration.

b.) PAN FIRE TESTS

The following table lists results of six different nozzles that were successll in extinguishing a 20 inch diameter pan fire (128 kW) of JP-5 aviation fuel. The pan was filled with 1/3 of a gallon of fuel which was allowed to bum for 1 minute before each extinguishment test. Each nozzle was 5 feet above and directly over the center of the pan. The tests were optimized for each nozzle to get a fair comparison. The tests were conducted in an open bay with an unlimited amount of available air to assure that the water mist, by itself, extinguished the fire. Table -1- indicates that the higher velocity mists of nozzles A, B and C have a significant advantage over lower velocity mists of nozzles D and E as measured from 1 ft below the nozzle. Note that the low and high flow air atomizing nozzles had a very low ALR's. Nozzle F has the highest velocity of the droplets when measured at **5 ft** below the nozzle. However, since it is a hydraulic nozzle, it utilizes high pressure water and the ambient air for atomization. Because of this lack of forced air, nozzle F uses consistently more water than any of the air atomizing nozzles except for Low Flow nozzle D to extinguish the pan. This illustrates that a major factor for fire extinguishment by water mists is the addition of air flow. In past tests, it was observed that higher velocity air requires less agent (by % volume) for extinguishment of pool fires (Hirst, Farenden, Simmons). Note that High Flow nozzle E is an air atomizing nozzle with lower velocity droplets, but it will consistently out perform Hydraulic nozzle F in pan fires. Additionally, High Momentum nozzles A and C have larger ALR's but they exhibit an even greater ability to extinguish the pan fires quicker using significantly less

	NOZZLE TYPE					
	Dual Fluid					Hydraulic
	High Momentum			Low Flow	High Flow	
	A	B	C	D	E	F
Water Pressure (psi)	15	18	18	60	80	550
Air Pressure (psi)	12	19	19	80	60	n/a
Extinguishment Time (sec)	2	15	5	155	6	8
Amount of Water (oz)	1.9	6.7	2.5	142.2	34	51.2
Amount of Air (SCF)	0.38	1.63	0.55	11.62	1.13	n/a
ALR	0.24	0.3	0.27	0.1	<0.1	n/a
Drop Sizes (microns)	**Measured at 1 ft in center of spray**					
Dn 10	<3	<3	<3	23	7	10
Dn 90	26	30	18	69	63	43
Dv 10	20.1	22.4	16.6	37.6	37.6	26.1
Dv 90	100.6	101.8	101.6	91.3	98.5	97.9
Sauter Mean Dia. (SMD)	38.2	40.7	28.8	58.1	59.2	44.2
Velocity (ft/s)	128.9	81.7	90.5	29.9	75.4	95.1
Drop Sizes (microns)	**Measured at 5 ft in center of spray**					
Dn 10	5	4	6	18	6	7
Dn 90	67	69.8	55	84	81	77
Dv 10	42.3	45.3	38.2	51.2	50.9	46.2
Dv 90	100.8	101.8	101.6	100.5	101.7	100.2
Sauter Mean Dia. (SMD)	65.9	67.5	56.6	72.8	72.6	69.6
Velocity (ft/s)	34.1	26.8	28.1	9.8	38.9	51.8

Each of the fine water mist nozzles demonstrated excellent cooling capability. The thermocouples mounted 3 inches above the fuel surface each read a decrease in temperature of over 1000°F in less than 10 seconds after the mist was turned on. The high momentum nozzle cooled the fuel below the flash point in 5 seconds using 4.8 oz. of water (reference figure -5-). The hydraulic nozzle (figure -3-) and high flow air atomizing nozzle (figures -4-) also cooled the fuel, rapidly, below the flash point in 14 and 12 seconds with 89.6 and 68 ounces of water, respectively. A steel bar was placed 6 inches above the fuel surface to demonstrate surface cooling. The surface temperature of the bar dropped an average of 270 °F for the three nozzles 10 seconds after mist operation.

For each test (figures -3- through -5-) the flames were completely extinguished in less than 10 seconds. The high momentum nozzle extinguished the entire pan in 2 seconds. The rim of the pan was the last to be extinguished, but the fire was not able to re-stabilize after the initial blast of mist. The hydraulic nozzle and high-flow air atomizing nozzle each required more time and water to extinguish the rim of the pan. Within two seconds the center portion of the pan was extinguished; however, flames continued to **burn** along the rim of the pan. With a height of 1 inch, the rim of the pan acted **as** a flame holder and was the last part of the fire extinguished in each case. Aircraft contain many such obstructions that may act as flame holders in the engine nacelles and dry bays. This fact again supports the need for small droplets at high velocity. In a highly cluttered area the droplets must be able to penetrate the flame with enough momentum for rapid

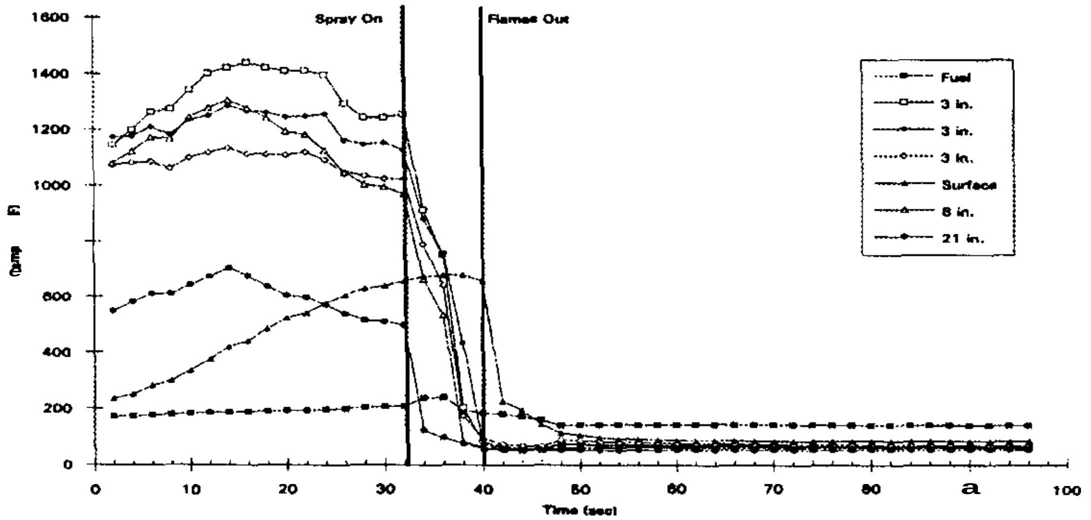

Figure -3- Hydraulic Nozzle F

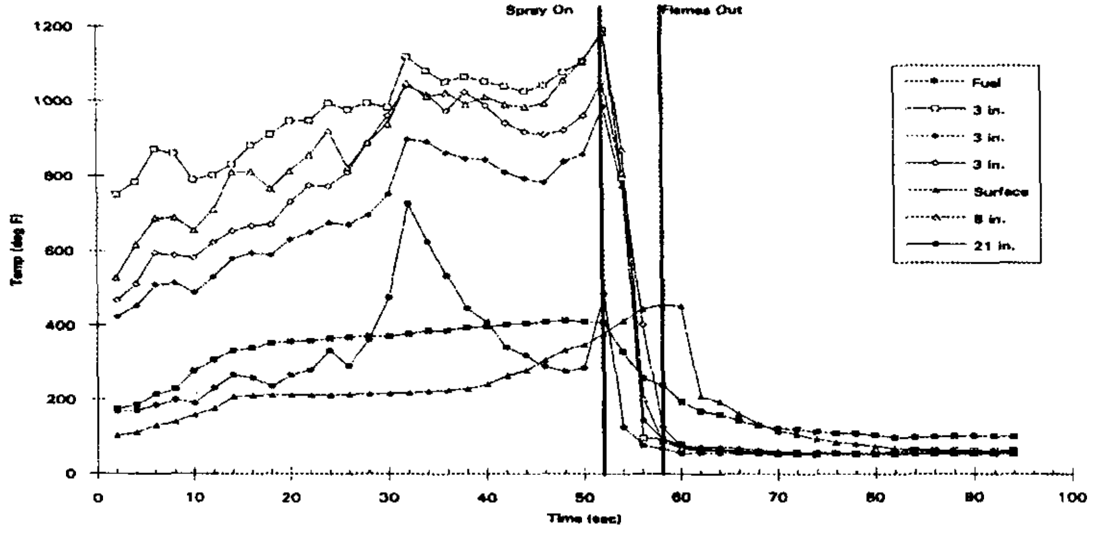

Figure -4- High Flow Nozzle E

extinguishment. This fact also stresses the importance of proper nozzle placement in an area that is highly cluttered. The Halon 1211 Extinguisher test demonstrated a lack of sufficient cooling (except when the agent contacted the thermocouple in liquid form as in two of the thermocouples located 3 inches above the pan). Both the fuel temperature and the surface temperature do not cool below the flash point of the fuel for the entire run.

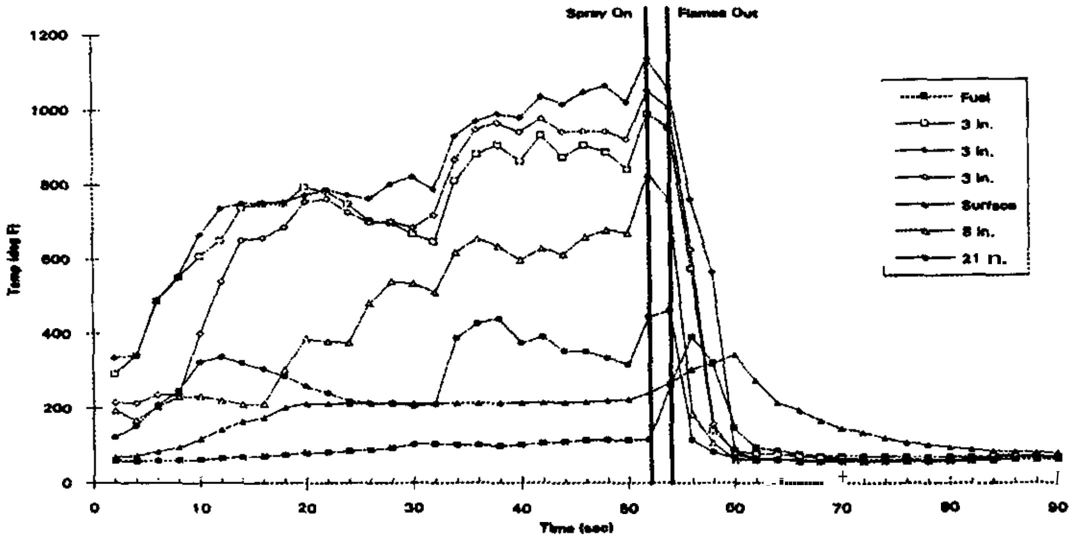

Figure -5- High Momentum Nozzle A

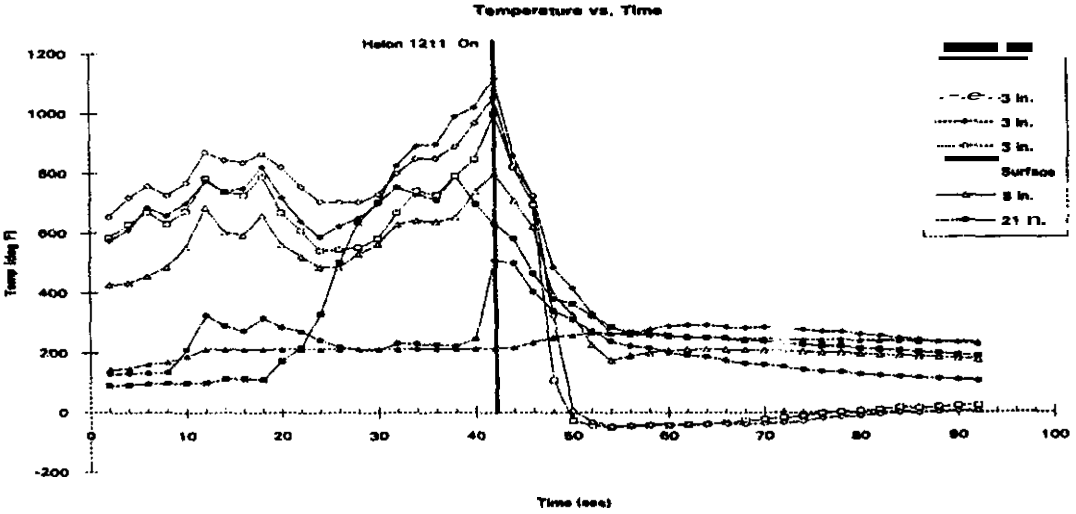

Figure -6- Halon 1211 Extinguisher

c.) HEATED WATER TESTS

It is known that by heating water, improved atomization results from the reduction in surface tension. Heaters were used to obtain boiling water for testing of both air atomizing and hydraulic nozzles. It was hoped that improved atomization would result by reducing the surface tension of the water via heating. However, results of the testing indicate only minor improvements in droplet characteristics in comparison to tests run at standard conditions. A lower Sauter mean diameter was noted consistently in the tests. This is may be due to the slightly increased spray angle of the heated water, especially since Sauter mean diameter is the volume to surface area ratio of the spray. Also, the high end of the frequency distribution number, Dn 90, was slightly reduced. Essentially, the spray becomes finer due to the higher temperature of the water. The mist was not hot upon discharge from the nozzle because subsequent cooling of the surrounding air instantly reduced the droplet temperature to ambient.

Further testing in this area will be conducted using pressure vessels and superheating the water. It has been learned that the superheating of water is very advantageous to explosion suppression. In fact, there are commercially available systems that produce this type of high momentum mist. They operate by heating water above its boiling point and increasing its liquid heat content, temperature and pressure. The energized liquid will self propel, using only a fraction of the stored energy. The remaining thermal energy explodes the water mass into droplets. The sudden energy release gives additional velocity and provides rapid dispersion of the fine water mist. This type of system is a major advantage for momentum (and velocity), dispersion and distribution of the mist (O'Connell).

FUTURE TESTING

The Naval Air Warfare Center, Warminster will be conducting full scale engine nacelle tests this summer using a J-79 engine from an F-4 aircraft. Also, the use of superheated water will be explored for applications in engine nacelles and dry bays. Additionally, explosion tests will be conducted to refine the response time mechanism for our initial design. These preliminary explosion tests will lead to full scale dry bay testing using water mist. Testing of several additives will be conducted in our environmental chamber, to verify performance at extremely cold temperatures. However, it is known that these solutions can be extremely corrosive.

CONCLUSIONS

From testing it is observed that Fine Water Mist nozzles must have a sufficient number of small droplets moving at high velocity to penetrate the flames and extinguish fires quickly. Nozzles that produce the highest velocity and the largest number of small droplets in the mist will be the most successful.

From testing it has been observed that: 1.) air atomizing nozzles are more efficient in extinguishing class B fuel fires typical to aircraft (pan fires and spray fires) due to the advantage of the entrained air flow. Subsequently, one drawback to air atomizing nozzles is the fact that they require an additional storage bottle and piping for the air lines. However, it has been demonstrated that a 128 kW pan fire can be extinguished in 2 seconds with 2 ounces of water in optimized tests. This occurs consistently and in a highly efficient manner with very low pressures in an open bay. Further, 1 mW spray fires were extinguished with small amounts of water in a test enclosure. The fact that low pressures and very small amounts of water were used successfully illustrates that air atomizing nozzles are a viable candidate for Fine Water Mist systems for aircraft applications. 2.) Heating water to boiling adds no major advantage. 3.) Full Fine Water Mist dispersion has been demonstrated in 125 msec.

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