False Deck Development Testing of Hybrid Nitrogen – Water Mist Fire Suppression Systems

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1.0 INTRODUCTION

Reduced manning on Naval vessels require automated fire suppression systems to compensate for the reduced size of damage control parties. Fine water spray or water mist systems are attractive from a total ship protection standpoint. Application of this technology to electronics spaces is problematic in terms of collateral damage to equipment, performance for involved cabinets, and performance in sub-floors. A previously conducted fire hazard analysis identified gaseous agent systems as the system of choice for critical/high value spaces in a peacetime fire scenario [1]. However, in wartime scenarios where the enclosure integrity cannot be assured, or the primary fire threat is in an adjacent space, the effectiveness of gaseous agent systems are severely compromised. A recent analysis of protection options for the DD(X) class destroyer indicates that there is not an optimum system when all factors of manning, automation, and performance are considered for both peacetime and war time scenarios [2].

The concept of an inert gas/water mist hybrid fire suppression system was proposed to address this issue [3]. The proposed technology involves the combined use of fine water spray and inert gas fire suppressants (e.g. nitrogen). The system would have the capability to:

1. Discharge fine water spray from open or fusible element heads;
2. Discharge a combination of water and inert gas in variable ratios to obtain desired gas/water concentrations, drop sizes, spray momentum, flow rates; and
3. Discharge dry gas through the same system piping at selected compartment, cabinet, or false deck level.

The initial challenge was to characterize the performance of water/gas mixtures. The electronic space sub-floor was selected since it provides both in-space and adjacent space fire challenges. Results from a sub-floor scenario should be scaleable to large volumes, e.g. an entire electronic space.

This investigation is part of the Advanced Damage Countermeasures efforts of the Office of Naval Research and the Naval Research Laboratory.

2.0 OBJECTIVE

The objective of this investigation was to develop the system parameters, independent of hardware, that correlate to effective fire protection, in terms of both extinguishment of fires within the sub-floor, and protection from exposure fires below the sub-floor.

3.0 APPROACH

This investigation was broken into two main aspects. The first aspect was the extinguishment of fires within the sub-floor space. The approach for this aspect consisted of developing the non-hardware dependant system parameters for the hybrid system that results in extinguishment of the test fires. These non-hardware dependant parameters included water mist suspended concentration, water mist drop size, nitrogen concentration and nitrogen discharge time.

Preliminary theoretical investigation into the hybrid system requirements revealed a linear relationship between the water mist concentration and the nitrogen concentration requirements [4,5]. The results of this preliminary investigation are given in Figure 1. In this investigation, the water mist is assumed to be 100% efficient in that all the mist reaching the fire is vaporized and raised to the flame temperature absorbing the energy output of the flame, and the nitrogen reduces the amount of oxygen available to the flame reducing the amount of energy produced, until a flame temperature of 1600 K cannot be maintained and the fire is extinguished.

The application rate required to maintain a given suspended water mist concentration is equal to the fall out rate of the mist due to gravity plus that lost due to interaction with the enclosure boundaries and other surfaces within the enclosure. Figure 2 illustrates the relationship between the minimum required mist application rate and nitrogen requirements [4,5].

The second aspect of this investigation was the boundary cooling and radiation absorbance provided by the water mist in protecting from an exposure fire below the sub-floor. The effects of the water mist application can be approximated through an estimate of the mist application rate required to limit the temperature in the sub-floor as shown in Figure 3. These requirements can be estimated through an energy balance in the sub-floor as illustrated in equations (1) and (2):

If $T_{SF} <= T_{sat}$

$$Q_{Fire}=(\psi\Delta Hv+C_{H2O,L}(T_{SF}-T_{H2O,amb}))Q_{mist} \quad (1)$$

If $T_{SF} > T_{sat}$

$$Q_{Fire}=(\Delta Hv+C_{H2O,L}(T_{Sat}-T_{H2O,amb})+Cp_{H2O,V}(T_{SF}-T_{sat}))Q_{mist} \quad (2)$$

Where T_{SF} is the temperature in the sub-floor [K], $T_{H2O,amb}$ is the ambient water temperature [K], Q_{Fire} is the heat transferred into the sub-floor due the below deck surface [kW], ψ is the fraction of the water mist that is vaporized, Q_{mist} is the application rate of the mist (water only) [kg/sec], $Cp_{H2O,V}$ if the heat capacity of water vapor [kJ/kg K], and $C_{H2O,L}$ is the heat capacity of liquid water [kJ/kg K]. Note, this energy balance assumes that all the non-vaporized mist exits the enclosure at the sub-floor air temperature, ignores the effects of air movement into or out of the enclosure, and no heat loss through the unheated compartment boundaries. The fraction of the mist vaporized is also a function of the sub-floor temperature, which can be estimated as follows:

$$\psi = P_{v,T}/P_{atm} \qquad (3)$$

Where $P_{v,T}$ is the vapor pressure of water at temperature T [kPa] and P_{atm} is the atmospheric pressure [kPa].

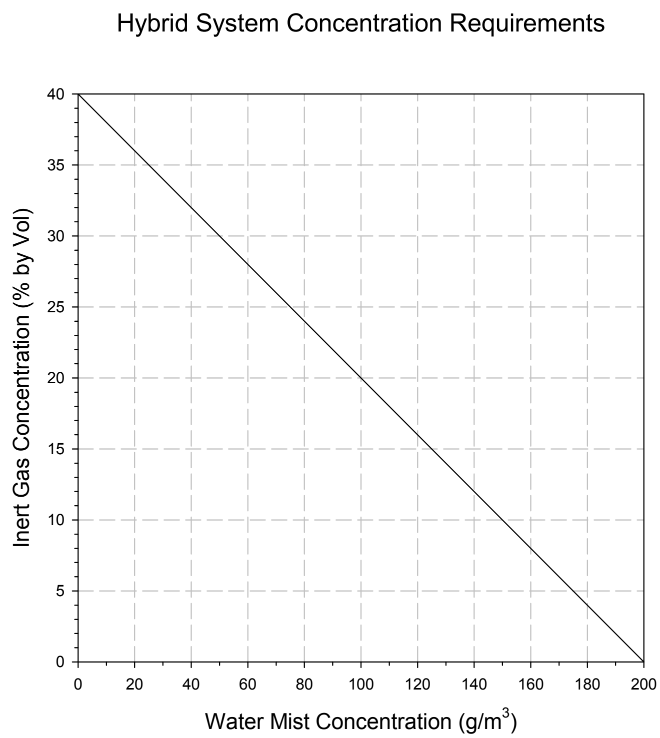

Figure 1 - Hybrid Nitrogen-Water Mist Concentration Requirements

System Parameters Based on a Flame Temperature Correlation

Assume Limiting Adiabatic Flame Temperature = 1600 °K

Figure 2 - Minimum Application Rate to Maintain Desired Water Mist Concentration as a Function of Drop Size

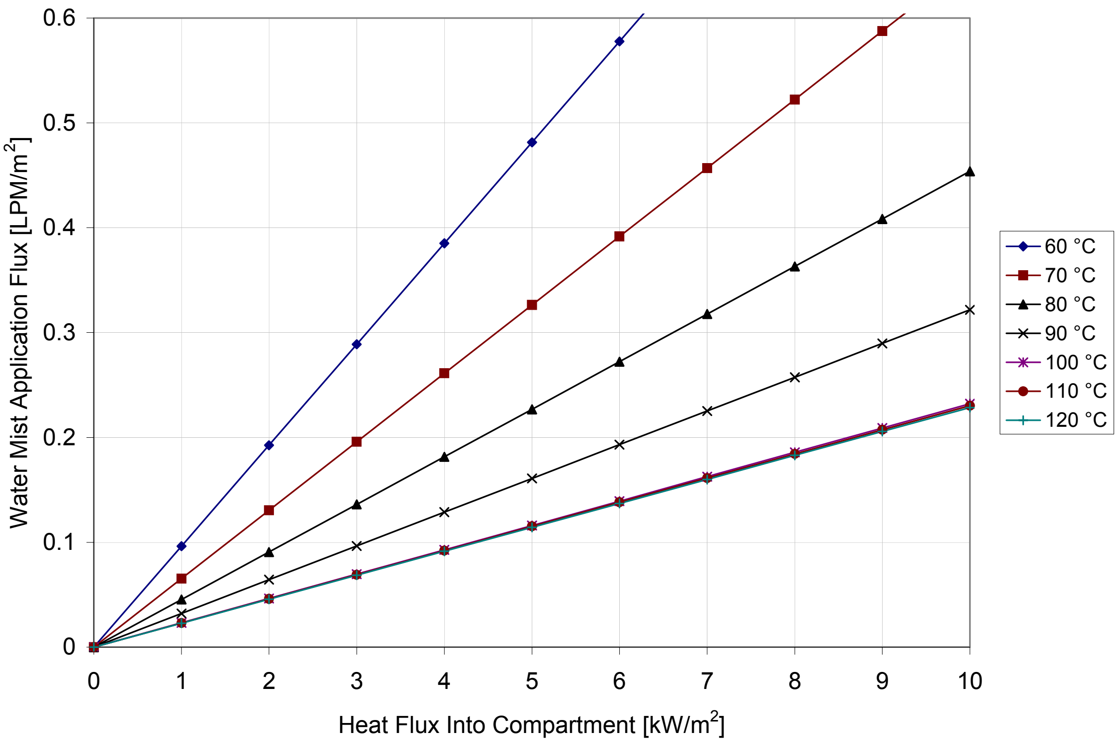

Figure 3 – Required Water Mist Application Flux Required to Limit Sub-Floor Temperature as a Function of the Below Deck Fire Exposure Referenced to Heated Deck Surface Area

4.0 TEST SETUP

4.1 Test Enclosure

A simulated false deck 2.0 x 1.9 x 0.3 m (6.5 x 6.1 x 1.0 ft) was constructed from 6.7 mm (1/4”) thick steel plate over an angle iron frame as shown in Figures 4 through 6. The top deck consists of nine 0.61 x 0.61 m (2 x 2 ft) panels that can be lifted off in order to gain access to the sub-floor area.

The simulated false deck was supported 0.61 m (2 ft) above the ground to facilitate below deck heating. This heating was accomplished with nine propane burners located 7.6 cm (3 in) below the lower deck surface as shown in Figure 7. Skirts, 0.3 m (1 ft) were attached to two adjacent sides below the deck level of the mock-up to reduce the convective losses from the burners.

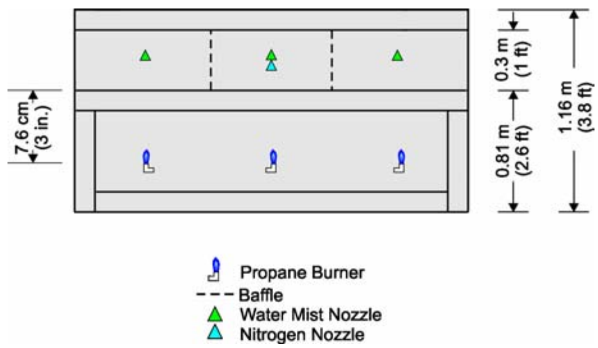

Figure 4 - Elevation Schematic of Simulated False Deck/Sub-Floor

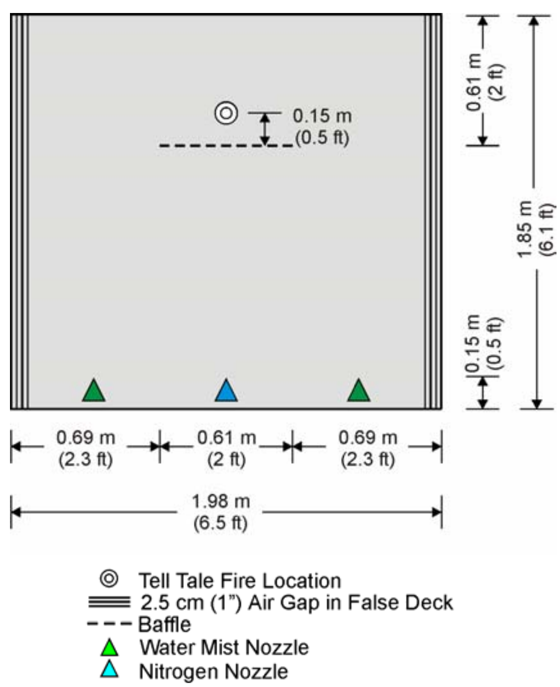

Figure 5 - Plan Schematic of Simulated False Deck/Sub-Floor

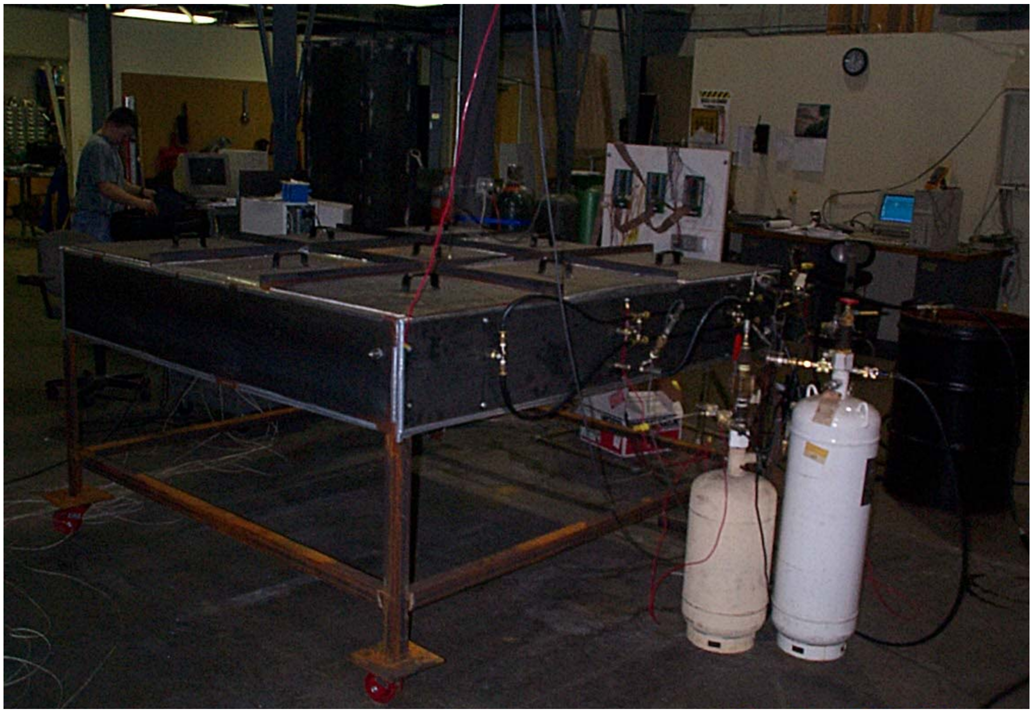

Figure 6 - Photograph of Test Enclosure

Figure 7 - Photograph Showing Below Deck Heating Burners

4.2 Fire Scenarios

Two fire scenarios were utilized during these tests. The first of these involved a "telltale" n-heptane can fire. The telltale can fire was similar in construction to that specified by Underwriters Laboratories in their clean agent standards UL-2127 [6] and UL-2166 [7]. The cup was 7.6 cm (3 in) in diameter, had a wall thickness of 5.50 mm (.216 in) corresponding to schedule 40 steel pipe, 10 cm (4 in) in height and fueled with 120 ml of n-heptane floating on a water substrate to result in a 5 cm freeboard. The telltale cup was placed 15 cm (6 in) from a vertical baffle located 0.61 m (2 ft) from the back wall and 0.61 m (2 ft) in length. This location is shown in Figure 5.

The second fire scenario consisted of a plastic sheet array similar that utilized in UL 2127 [6] and UL 2166 [7]. This array was scaled down to utilize two 5 x 10 x 9.5 cm (2 x 4 x 0.375 in) sheets of polypropylene with 1.27 cm (0.5 in) gaps between the sheets. The array was held in place by one 6.8 mm (.25 in) all thread rod suspended from an angle aluminum frame. The array was ignited by 5 cm (2 in) square pan, fueled with 3 ml of n-heptane. The array was centered behind the baffle with the plastic sheets running parallel to the baffle. The center of the array was 15 cm (6 in) from the baffle.

4.3 Hybrid Water Mist and Inert Gas Systems

Five water mist generation methods were employed during these tests. The first consists of high-pressure hydraulic atomizing nozzles (Spraying Systems LN Series). These nozzles were used to generate the relatively course 100 micron drop size mists. These nozzles produce a 70^o to 90^o hollow cone spray pattern. In utilizing these nozzles, a gasoline powered pressure washer was utilized to supply the water to a three-nozzle manifold attached to the near end of the simulated sub-floor. The water mist system flow rate was controlled by upstream pressures and by the nozzle orifice size.

The second method utilized the same set-up as the first, except that the LN Series Nozzles were replaced with impingement style Bete Fog Nozzle PJ Series Nozzles. This results in a finer atomized, lower momentum water mist to be generated. Average drop size is approximately 25 microns.

The third method consists of a multi-orifice tube (Micro-Mist Water Mist System) located at mid-height of the front wall of the sub-floor and was utilized to generate the 25 micron drop size mists. The flow-rate and drop size was controlled by the pressure of the water at the nozzle. Each of the nozzles on the tube produces a 90^o full cone mist pattern. The gasoline powered pressure washer was utilized to provide water in this set-up as well.

The fourth method utilized air-atomizing nozzles (Spraying Systems SUE Series Nozzles) to generate the 50 micron drop size mists. These nozzles produce a 45^o flat fan pattern oriented parallel to the lower deck of the test enclosure. A three-nozzle manifold similar to the one utilized in the first technique was used with this technique. Note that air was utilized to atomize the water flow from these nozzles to allow the amount of nitrogen added to be controlled separately.

The fifth water mist system (NanoMist System) utilized an ultrasonic technique to generate the fine water droplets and an air stream to carry the generated droplets into the enclosure. The generated mist was introduced into the enclosure through a 10 cm (4 in) circular opening in a top cover plate 15 cm (6 in) from the front wall of the enclosure. The generate water mist has an average drop size of approximately 7 microns.

The nitrogen system consisted of a nominal 24.3 l (0.86 ft3) cylinder that discharged through a single nozzle located below the water mist nozzle(s). The discharge rate was controlled by the nozzle orifice size and the amount of nitrogen added was determined by the initial charge in the cylinder.

5.0 RESULTS AND DISCUSSION

5.1 Extinguishment Tests

Extinguishment tests were conducted with both the single n-heptane telltale fire and the polypropylene sheet array fire. In tests with the telltale fire, the fire was allowed a 60 second pre-burn prior to water mist system activation. In tests with the polypropylene array fire, the fire was allowed a 120 second pre-burn prior to water mist system activation. The cover plate directly above the test fire was removed during the pre-burn period and replaced just prior to water mist activation. With the exception of the nitrogen alone tests, the nitrogen system was activated 60 seconds after the water mist system. This allowed the mist to build up its concentration prior to nitrogen application. During the nitrogen alone tests, the nitrogen system was activated at the end of the pre-burn period.

The nitrogen system, by itself, was able to extinguish both the single telltale and the polypropylene array fires at a design concentration of 25% by volume. This concentration was lower than the cup burner value of 31% by volume [8], evidencing some help from oxygen depletion from the fire to cause extinguishment.

The results of the extinguishment testing with both the telltale fire and the polypropylene array are given in Figures 8 and 9. With the exception of the NanoMist System, none of the water mist systems tested was able to extinguish the single telltale fire or the polypropylene array fire by itself. This is consistent with the inside enclosure mist characterization tests where the mist concentration was measured to be much lower than the 200 gm/m^3 theoretical requirement.

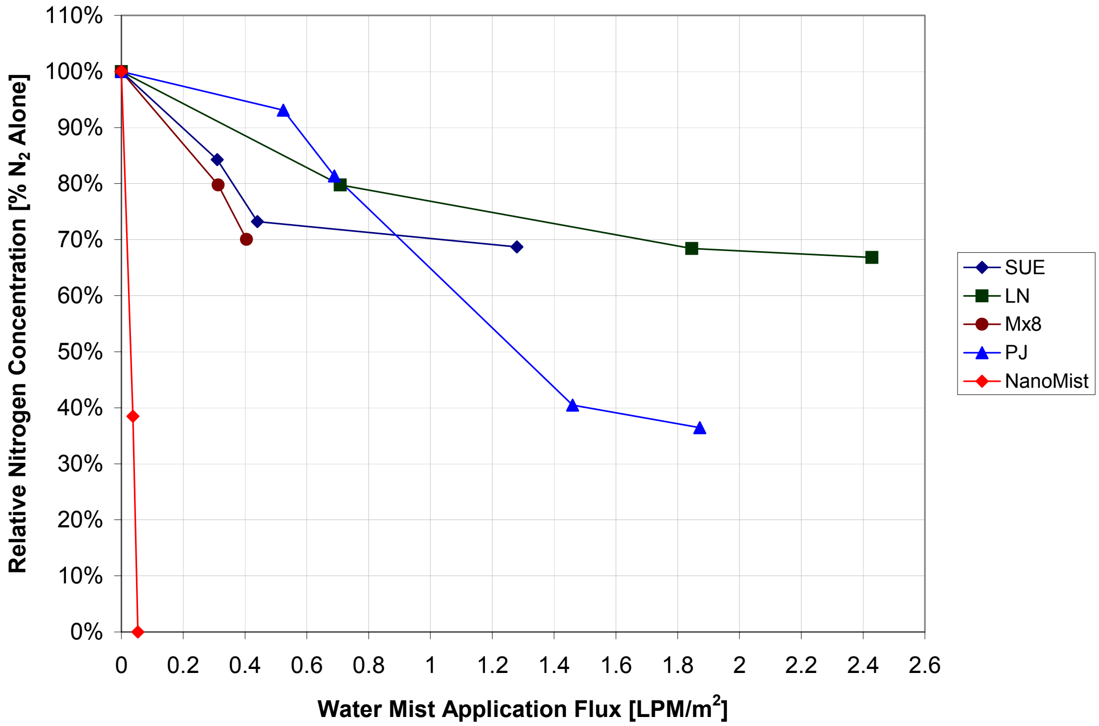

Figure 8 - Telltale Fire Extinguishment Results

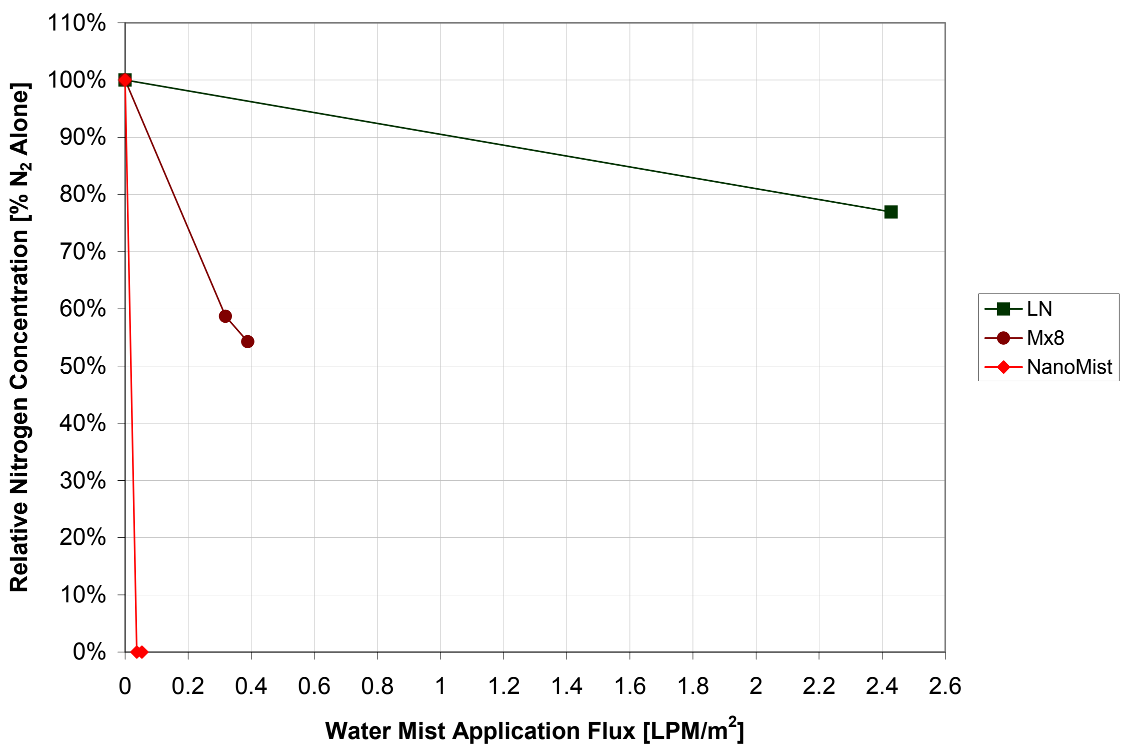

Figure 9 – Polypropylene Array Fire Extinguishment Results

5.2 Below Deck Fire Exposure Tests

During these tests, the propane flow to the burners was 21 SLPM (44 SCFH) for a total heat output of 30 kW (32 Btu/s) or 8.0 kW/m2 (0.78 Btu/ft2 s). The pre-heat time prior to activation of the water mist system was 20 min. The lower surface temperatures had reached approximately 350 C (662 F) by the end of the pre-heat period. The air temperatures in the center of the mock-up had reached approximately 140 C (284 F).

The results of these tests are summarized in Table 1. The water mist application caused a rapid decrease in the air temperature in the false deck mock-up. The amount of the reduction before leveling off was a function of the application as predicted from Figure 3. The measured air temperatures in the center of the mock-up during the below deck heating test is given in Figure 10.

The radiant heat flux measured at the top of the mock-up, showed a marked decrease as illustrated in Figure 11 upon system activation in all of these tests. The total heat flux, however, showed an increase upon system activation as illustrated in Figure 12. The increased total heat flux would, at least, appear to contradict the cooling effects of the water mist application in the sub-floor with respect to the heat transferred to the space above the sub-floor. This would result in the upper floor temperature heating up faster than it would have without the water mist application, however, the final temperature would be reduced to not exceed the air temperature in the sub-floor.

Table 1 – Below Deck Heating Summary

	Number of Nozzles or Misters	Water Flow		Air Flow		Water Concentration		Air Temp at Center of Mock-Up at System Activation		Final Air Temp at Center of Mock-up	
		Flow Rate	Flux	Flow Rate	Changes						
Type		[LPM]	[LPM/m^2]	[L/s]	[#/hr]	[%wt]	[g/m^3]	[^{o}C]	[^{o}F]	[^{o}C]	[^{o}F]
SUE-15 Air Atomizing Flat Fan 45^o Pattern	3	1.59	0.43	6.4	20.4			125	257	80	176
LN-8 Hollow Cone 91^o Pattern	3	9.3	2.52					125	257	53	127
MicroMist MX 8	12	1.5	0.41					140	284	85	185
NanoMist System	1	0.16	0.043	5.7	17.9	28.1%	469	150	302	134	273
	1	0.14	0.038	8.1	25.6	19.3%	287	130	266	120	248
	2	0.22	0.060	11.4	35.8	21.2%	322	135	275	93	199
	2	0.23	0.062	14.6	46.1	17.9%	262	147	297	106	223

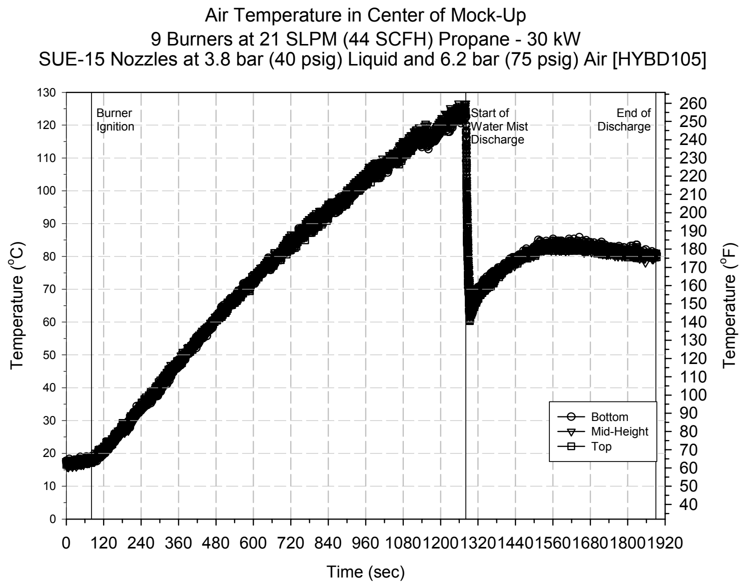

Figure 10 – Air Temperatures in the Center of Sub-Floor during Below Deck Heating Test with Air Atomization (SUE-15 Nozzles) – 8.0 kW/m^2 Exposure

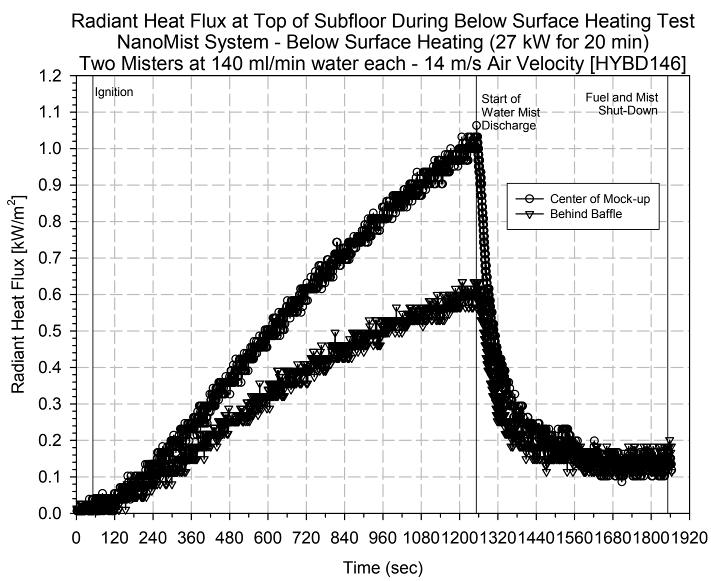

Figure 11 – Radiant Heat Flux at Top of Sub-Floor during Below Deck Heating Test with NanoMist System (Two Misters – Air Flow of 36 changes/hr) – 8.0 kW/m^2 Exposure

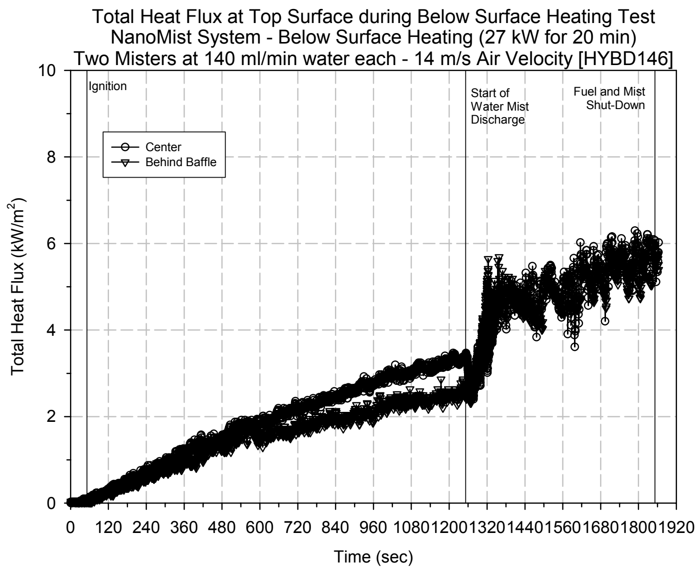

Figure 12 – Total Heat Flux at Top of Sub-Floor during Below Deck Heating Test with NanoMist System (Two Misters – Air Flow of 36 changes/hr) – 8.0 kW/m^2 Exposure

6.0 CONCLUSIONS

Five water mist systems have been tested, coarse atomization single fluid water mist system incorporating Spraying Systems LN Series Nozzles, fine atomization single fluid water mist system incorporating a Micro-Mist MX8 Nozzle Tube, single fluid water mist system employing impingement style Bete PJ Series Nozzles, air atomized water mist system incorporating Spraying Systems SUE Series Nozzles and the NanoMist System which incorporates an ultrasonic atomization technique with a carrier air stream. Only the NanoMist System was able to extinguish the telltale fire by itself. The system incorporating the PJ Series Nozzles was able to reduce the nitrogen requirements to 40% of that required utilizing nitrogen alone, but at an elevated application flux. The systems incorporating the LN Series Nozzle, the SUE Air Atomizing Nozzles and the Micro-Mist Nozzle tube provided an approximate 30% reduction in the required nitrogen to cause extinguishment by itself.

These water mist systems were able to moderate the temperatures with in the false deck/sub-floor area in the below deck fire exposure scenario. The temperature to reduced to below the normal boiling point of water, 100 ^{o}C. This ability is a function of the water mist application flux relative to the exposed heat flux through the deck.

7.0 CONTINUING INVESTIGATION

Continuing investigations include the "screening" tests in the false deck/sub-floor mock-up of dual fluid and single fluid water mist systems.

The mock-up will be scaled-up to 25 m^2 to 100 m^2, which will represent a scaling ratio of 6:1 to 25:1 in area. Emphasis would be on refining developed design rules and system optimization. Impact of obstructions in the sub-floor and fires involving electrical cable bundles will be examined during the scaled-up testing.

Continuing investigations also include system integration of the hybrid water mist – nitrogen fire protection concepts to the fire protection schemes for shipboard electronics spaces.

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