STUDY OF AN ULTRA-FINE WATER MIST SUPPRESSION SYSTEM FOR SPACECRAFT FIRES

Angel Abbud-Madrid, James D. Watson, Jess G. Whittington, and J. Thomas McKinnon
Center for Commercial Applications of Combustion in Space
Colorado School of Mines, Golden, CO 80401
Ph: (303) 384-2300, Fax: (303) 384-2327, e-mail: aabbudma@mines.edu

Jean-Pierre Delplanque
Mechanical and Aeronautical Engineering
University of California, Davis, CA 95616-5294
Ph: (530) 754-6950, E-mail: delplanque@ucdavis.edu

ABSTRACT

An experimental investigation on the effectiveness of various suppressant agents in spacecraft fires under normal-gravity conditions is conducted. Ultra-fine water mist driven by air or by nitrogen is compared to carbon dioxide and nitrogen to evaluate their performance to suppress and extinguish fires involving energized wires, electrical components on circuit boards, and cloth. Extinction time and suppressant amount are used as a measure of agent effectiveness. On a mass-basis, ultra-fine mist driven by air is found to be more effective than carbon dioxide and nitrogen, with the exception of highly energized burning wires, where ultra-fine mist is used to cool the hot wire, as well as to extinguish the small remaining fire. In this case, ultra-fine mist driven by nitrogen performs similarly to the gaseous agents. The low momentum and pseudo-gas properties of ultra-fine mist with lower-than-10-μm droplets are also more effective than the high-momentum and larger droplet sizes generated by high-pressure water-mist sprays.

INTRODUCTION

The renewed emphasis on the human exploration of space is focusing on the development of new spacecraft like the Crew Exploration Vehicle (CEV) and on future planetary habitats for the long-term settlement of the Moon and Mars. The development of these new programs has consequently prompted a reevaluation of current fire suppression systems on spacecraft and it has motivated a feasibility study for possible replacement technologies. The challenges to the designer of a new fire suppression system for space applications are many and sometimes unique to the type of environment encountered outside the Earth's atmosphere and in other planets. The use of a light, non-toxic, and efficient suppressant capable of rapidly extinguishing a fire in a confined space with minimum generation of toxic byproducts, low impact on visibility, and with fast and easy cleaning and recovery procedures are among these challenges. For long duration missions, the ability to store the agent at low pressures, avoid leakage, and refill the extinguisher with a suppressant easily available on the spacecraft is also of primary concern. In selecting such a suppressant agent, it is necessary not only to look at its extinction efficiency as compared to other options, but it is also important to study the dispersion properties of the agent in partial gravity environments and in the presence of complicated geometries with a variety of obstacles, ventilation sources, and fire scenarios.

Responding to the many challenges mentioned above, a comprehensive study of the fire suppression properties of a variety of single- and multi-phase agents in spacecraft and extraterrestrial habitats is being conducted at the Center for Commercial Applications of Combustion in Space at the Colorado School of Mines. The purpose of this project is to investigate the effectiveness of these suppressants in single or mixed-agent configurations on different fire scenarios, geometries, and low-gravity conditions evaluated numerically and experimentally and compared to other fire-fighting agents currently used in spacecraft fire-safety systems. The modeling effort consists of developing detailed sub-models of the fire source, the suppression agent generation and distribution, and the radiative shielding of the suppression agent. These sub-models will then be integrated into a high-fidelity fire suppression model. Finally, a reduced order model will be developed to minimize the computational requirements, yet retain the simulation capabilities of the original formulation.

In a preliminary evaluation of the various potential suppressant agents available [1], this study found that water mist (by itself or in combination with other gaseous agents) appears to be an excellent candidate to address most of the above challenges. On a per unit-mass basis, water is as effective as Halon 1301, the agent currently used in the Space Shuttle, while water is more effective than carbon dioxide (CO_2), the agent onboard the International Space Station. Water is also non-toxic, non-corrosive, readily available in spacecraft for multiple uses, and water in the form of ultra-fine mist may act as a total flooding agent in reduced gravity. In addition, advantage may be taken of the rapid evaporation of ultra-fine mist for its use in fighting electrical fires. Finally, agent cleanup operations may be achieved with dehumidifiers in the ventilation system. Consequently, the suppression properties of water mist are currently being investigated and compared to other potential candidates in the search for new fire extinguisher systems for the next generation of spacecraft.

As a continuation of the initial tests conducted last year with high-momentum water mists with droplet size distributions with mean diameters in the 20 to 40 μm range [2], this paper presents the results from a series of tests with ultra-fine water mist clouds (mean diameter of 8 μm) driven by air or by nitrogen (N_2), and their effectiveness compared to single-fluid agents such as CO_2 and pure N_2. All these extinguishing fluids are tested for a variety of typical fires to be encountered in spacecraft such as energized wires, electrical components on circuit boards, and cloth. The normal-gravity comparison has been based not only on extinguishment time and mass of agent used, but also on their overall performance and behavior in the extinction process, as well as the implications of their use under spacecraft conditions.

EXPERIMENTAL APPARATUS AND PROCEDURES

Three sets of experiments have been performed in a 44-cm wide, 25-cm high, and 51-cm deep container with similar characteristics to the Space Shuttle Mid-deck Locker, as described in a previous publication [2] and as shown in Fig. 1. The different experiments correspond to the three fire scenarios that have been identified as the most probable to occur in a spacecraft: a) overheated wire, b) burning element on a circuit board, and c) burning cloth. For each case, the suppressant agents used are: a) ultra-fine mist, b) carbon dioxide (CO_2), and c) nitrogen (N_2).

FIRE SCENARIO 1: OVERHEATED WIRE

The overheated wire suppression experiments are conducted with a 15-cm long, polyethylene-insulated #20 wire with a high current flowing through it. The behavior of the burning insulation is observed and flame-spread rates for a downward propagation configuration are measured. Although these tests are conducted in normal gravity with a buoyancy dominated flow field, these downwardly propagating flames exhibit a well-behaved flame front reminiscing of propagation under low-gravity conditions. In contrast, flames propagating in the horizontal and upward direction are plagued with instabilities and turbulence generated by buoyancy. A measure of the time from ignition to extinction of the flame, the mass of insulation burned, and the heat of combustion of polyethylene gives an average fire size of 72 W. The electrically heated wire raises the surface temperature of the wire insulation to over 100C with an electrical current of approximately 35 amps, without leading to ignition. The electric power supplied to the wire is kept constant during the test at 450 W. Higher power levels only cause the wire to distort and melt away the insulation without a transition to flaming. Thus, an accurately regulated constant-power electrical source is needed to preheat the wire and sustain a flame initiated by an external ignition source.

In a typical test, the sample wire is held vertically between two large copper clamps. The high current is applied and the wire is allowed to heat for 30 seconds before it is ignited near the top clamp with a propane lighter. After propagating for 2.5 cm, the burning time is measured for the next 5 cm to calculate the flame speed. The average downward flame speed is 0.6 mm/sec.

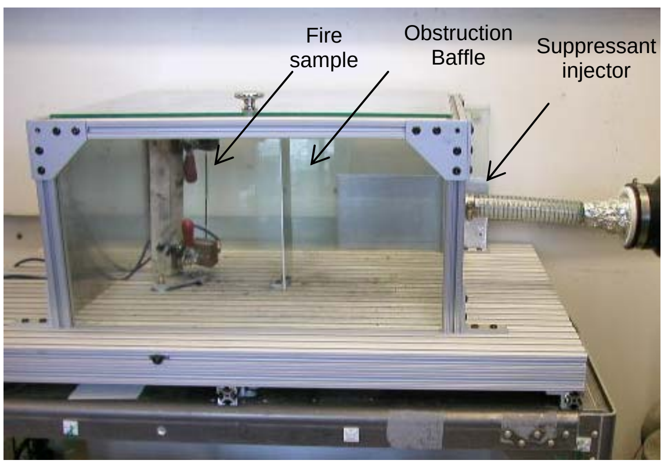


Figure 1. Experimental apparatus for spacecraft fire suppression tests based on the dimensions of a typical Space Shuttle Mid-deck Locker.

FIRE SCENARIO 2: BURNING ELEMENT ON A CIRCUIT BOARD

An electronic component burning on a circuit board inside a tightly packed compartment with electronics is another potential fire hazard onboard spacecraft. For this scenario, a 2-cm diameter and 5-cm long PMMA rod is slightly heated by an electric cartridge providing 25 W of constant heating power. As in the case of the wire, heating is necessary to keep the flame propagating down the rod. Horizontal propagation is measured to avoid the massive dripping on the sample experienced on vertical or downward flame propagation. The average flame speed is 0.4 mm/s and the average fire size is 250 W. The component is attached to the side of a rectangular baffle facing opposite to the suppressant agent injection point to simulate a highly obstructed fire, as it may occur in the avionics section of the spacecraft. The test starts by heating up the rod and then lighting it with a propane torch on one extreme. The heating power is kept on during the entire test to simulate an energized burning element and to study a worst case fire-suppression scenario.

FIRE SCENARIO 3: BURNING CLOTH

Besides the two energized fires described above, other non-energized potential fires may involve the various solid fuels onboard the spacecraft, such as astronaut suits, cloth, paper, and plastic materials. To simulate this type of fire, a 2.5-cm wide by 10-cm long pure-cotton rag is used with top ignition and downward propagation as with the wire tests. An average flame speed of 0.5 mm/s is measured for an average fire size of 200 W. Contrary to the other two fire scenarios, in this case there is no external heating and the cotton rag is allowed to burn on its own as the suppressant agent is applied.

All of the above fires are subjected to three different suppression agents consisting of 1) N_2, 2) CO_2, and 3) ultra-fine mist driven by air. Only in the case of overheated wires, ultra-fine mist is also driven by nitrogen. Since the weight of the agent is of primary concern in the system design, all agents are injected at identical mass-flow rates of 0.2 g/s (low), 1.0 g/s (medium), or 2.0 g/s (high). As shown in Fig. 1, the burning samples are located at 40 cm from the suppressant injector, while a 16-cm wide, 25-cm high baffle is placed between the injector and the sample at 25 cm from the injector. This last configuration is used to provide an extremely difficult path for the suppressant to reach the fire. For the burning PMMA element, the rod is attached to the baffle on the side opposite to the incoming stream of suppressant agent. In addition, two one-inch diameter ventilation ports located behind the sample (not shown in Fig. 1) are kept open to provide an easy deflection of the agent to the outside of the chamber, making the path of the agent to the fire even more difficult. The ultra-fine mist unit generates an average droplet size of 8 μm and the mist is propelled outside the unit into the test apparatus by either air or nitrogen at a 20% water load by mass. The CO_2 and N_2 gases are both of 99.9% purity and are injected at 25 C. For all tests, extinction times and suppressant amounts are measured and a minimum of 15 tests are conducted for each case to provide statistically significant results.

RESULTS AND DISCUSSION

The experimental results obtained from the suppression tests conducted for the three fire scenarios and the three suppressant agents mentioned above show different behavior depending on each fire-agent combination. The majority of the results below are given for the medium mass-flow rate case of 1.0 g/s, where clear suppression and extinction are observed for all cases. As explained below, the two gaseous agents have difficulty extinguishing the fires at the low mass-flow rate, while introducing several flow dynamics complications at the higher flow rate.

FIRE SCENARIO 1: OVERHEATED WIRE

The suppression results obtained for overheated wires are presented in Table 1. As expected for agents with similar heat capacities per unit mass, the extinction time for CO_2 and N_2 is quite comparable. Interestingly, ultra-fine mist driven by air is not as effective as the gaseous agents for this fire scenario, taking considerably longer to extinguish the fire. This apparent weakness is in sharp contrast to the advantages of using water mist in the burning-element and burning-cloth cases described below. This discrepancy may be explained by a combination of two factors: a) the overwhelming heat generated by the electrical power applied to the wire (450 W), almost an order of magnitude higher than the fire power, and b) the "small-fire syndrome," a phenomenon frequently observed in weekly burning fires suppressed with water, where the small fire is able to survive with barely adequate levels of oxygen by reducing the water evaporation rate below a critical value. It is believed that these two reasons may explain why the water droplets are not being efficiently used to put out the fire. During the experiments, it is observed that the mist quickly reaches the fire after less than 5 seconds from injection and immediately suppresses it by significantly diminishing its size and its spread rate. Nevertheless, after that rapid initial suppression, some amount of water mist appears to be spent cooling the hot copper wire by evaporating around it, another group of droplets just re-circulates inside the test chamber, while the rest of the droplets concentrates near the small fire.

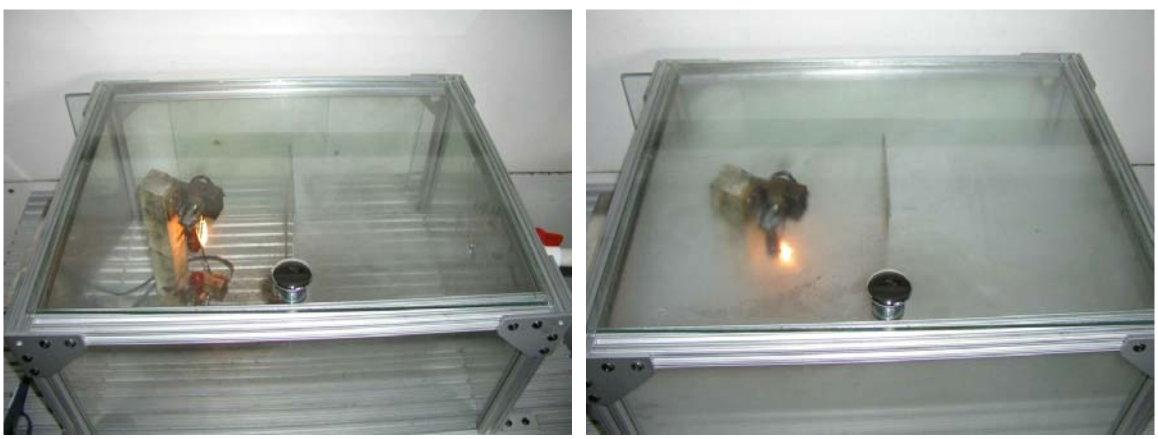
To verify this hypothesis, the ultra-fine mist is introduced at the slow mass-flow rate of 0.2 g/s, and as shown in Table 1, 65% less water is needed to put out the fire even though it takes much longer to extinguish it, indicating that at higher mass-flow rates, the water is not effectively used to control the fire (on a mass basis). If extinction time is the main design parameter, it is interesting to note that although it takes more than three times longer to extinguish the fire, the final position of the flame at the low mass-flow rate case is just a few millimeters past the spot where the flame extinguishes under the medium mass-flow rate case. Obviously, ultra-fine mist acts as an extremely efficient suppressant, but it has a more difficult time to completely extinguish the small remaining flame, as compared to the gaseous agents.

To verify the "small-fire syndrome" hypothesis, 0.5 g/s of ultra-fine mist are introduced in the chamber driven by 0.5 g/s of N_2. As seen from the numbers listed in Table 1, this combination effectively cools down the wire, rapidly suppresses the spread rate of the flame, and quickly puts out the remaining small fire. For the water-mist/N_2 combination, both the extinction time and the total amount of suppressant used to extinguish the flame are comparable to the values obtained for the gaseous agents. It is important to point out that neither CO_2 nor N_2 are capable of suppressing the fire at mass-flow rates lower than 1 g/s. Under these conditions, most of the time the wire breaks before the flame is extinguished, and on other occasions the insulation completely melts down and falls to the bottom of the chamber, making it impossible to quantify the effectiveness of the agent. For this particular case, the unique suppression properties of water mist in conjunction with the oxygen-depletion attributes of N_2 result in a superior combination with excellent performance. Pictures of the flame at two different stages during the water-mist injection are shown in Fig. 2.

Table 1. Measurements of time and suppressant amount listed in order of effectiveness to extinguish a flame propagating down an energized #20 polyethylene-insulated wire (overheated-wire fire scenario) with several suppressant agents and mass-flow rates.

SUPPRESSANT	TIME TO EXTINCTION (seconds)	AMOUNT OF SUPPRESSANT (grams)
(1.0 g/s)		
N_2	13.3	13.3
CO_2	14.1	14.1
Ultra-fine mist + N_2	14.3	14.3
Ultra-fine mist	25.3	25.3
(0.2 g/s)		
Ultra-fine mist	82.3	16.5

Note: The standard deviation for the extinction time and suppressant amount for N_2, CO_2, ultra-fine mist + N_2, and ultra-fine mist tests at 1.0 g/s is 1.77, 1.82, 1.74, and 1.95 respectively, while for the ultra-fine mist at 0.2 g/s is 1.81.



(a) (b)

Figure 2. Top view of the experimental apparatus showing the flame at the top of the vertical test wire, the baffle in front of it, and the ultra-fine water mist, (a) immediately after injection, and (b) five seconds after the initial injection with ultra-fine mist surrounding the flame.

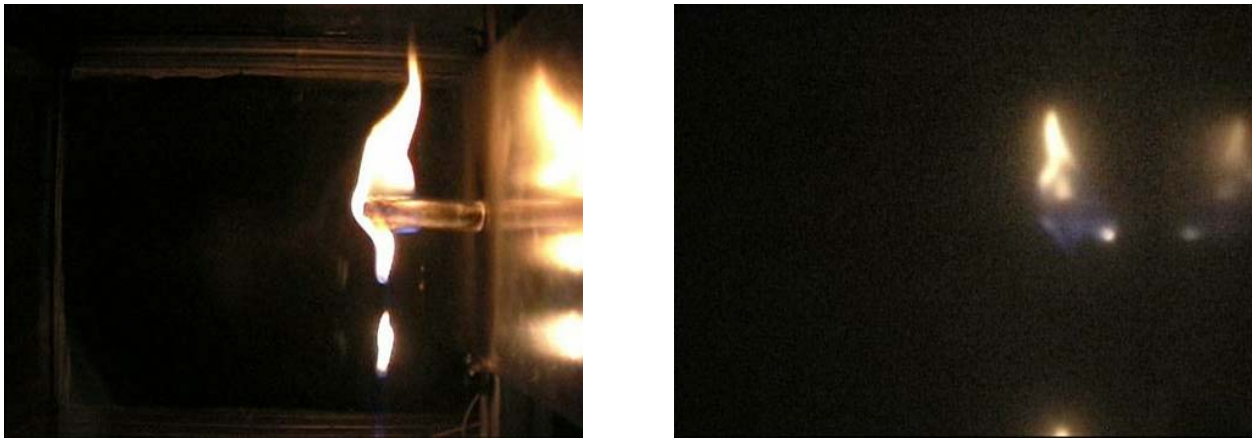
FIRE SCENARIO 2: BURNING ELEMENT ON A CIRCUIT BOARD

The suppression results obtained for the simulated case of a burning element on a circuit board are presented in Table 2. In this case, only 25 W are applied to the heater cartridge to preheat the PMMA rod, allowing the water droplets to concentrate on putting out the fire instead of cooling the heated element. Consequently, ultra-fine mist gives the best results based on time and suppressant amount, followed closely by the two other gaseous agents. As with the overheated wire case, the ultra-fine mist is also introduced at the slow mass-flow rate of 0.2 g/s, and as shown in Table 2, less water is needed to put out the fire even though it takes much longer to extinguish it. In addition, although it takes more than four times as long to extinguish the fire, the final position of the flame at the low mass-flow rate case is just a few millimeters past the spot where the flame extinguishes with the medium mass-flow rate.

Table 2. Measurements of time and suppressant amount listed in order of effectiveness to extinguish a flame propagating horizontally along a PMMA cylindrical rod (burning-element-on-a-circuit-board fire scenario) with several suppressant agents and mass-flow rates.

SUPPRESSANT	TIME TO EXTINCTION (seconds)	AMOUNT OF SUPPRESSANT (grams)
(1.0 g/s)		
Ultra-fine mist	13.7	13.7
CO_2	13.8	13.8
N_2	17.4	17.4
(0.2 g/s)		
Ultra-fine mist	60.5	12.1

Note: The standard deviation for the extinction time and suppressant amount for ultra-fine mist, CO_2, and N_2 tests at 1.0 g/s is 1.62, 1.92, and 1.72 respectively, while for the ultra-fine mist at 0.2 g/s is 1.74.



(a) (b)

Figure 3. A flame propagating horizontally along a PMMA rod located behind the obstruction baffle and preheated by an electric cartridge, (a) before the injection of a suppressant agent, and (b) suppressed by ultra-fine mist surrounding the rod and just prior to extinction.

This is another case where fire suppression is effectively and quickly accomplished by the ultra-fine mist with the rest of the time spent to completely extinguish the small remaining flame. The gaseous agents are again incapable of putting the fire out at the low mass-flow rate with the flame completely consuming all the PMMA material. Pictures of the flame before and after the injection of the water mist are shown in Fig. 3.

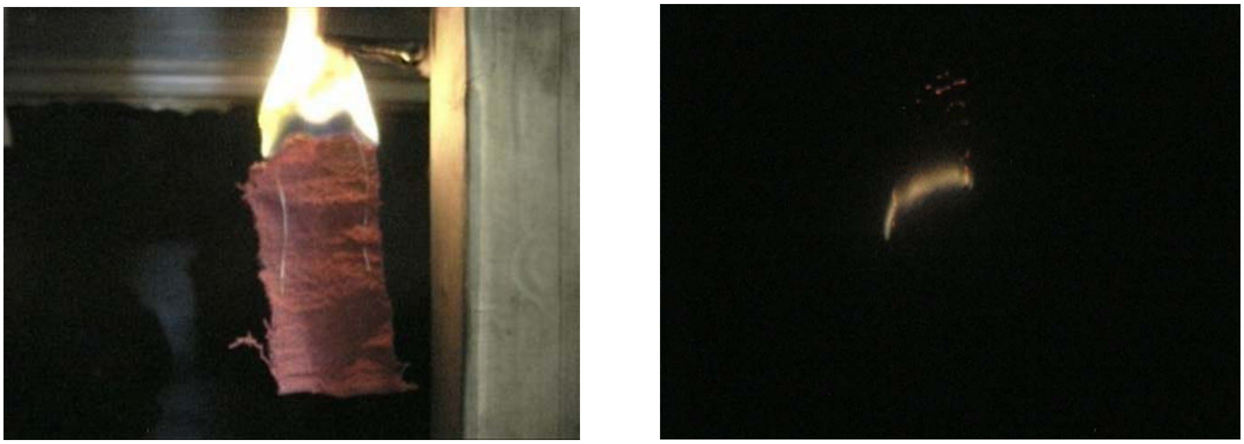
FIRE SCENARIO 3: BURNING CLOTH

The suppression results obtained for the burning cloth case are presented in Table 3. This is a representative example of a fire burning completely unaided by any external heating. As a result, ultra-fine mist clearly is the most effective suppressant as compared to the CO_2 and N_2 gases. On a mass basis, its effectiveness its further enhanced when ultra-fine mist is introduced at the low mass-flow rate of 0.2 g/s, while the gaseous agents are incapable of putting the fire out at this lower rate. For the high mass-flow rate case, CO_2 and N_2 not only introduce convective currents that would enhance the flame strength under low-gravity conditions, but they also blow away the smoldering embers that remain in the post-flame zone on top of the burning rag. An added benefit of using water droplets in this particular case is the ability of the water to extinguish the smoldering embers considerably faster than the other two agents. This is due to the moisture absorbed by the cloth that forms an obstructive barrier for further flame propagation. Pictures of the flame before and after the injection of the water mist are shown in Fig. 4.

Table 3. Measurements of time and suppressant amount listed in order of effectiveness to extinguish a flame propagating down a cotton rag (burning-cloth fire scenario) with several suppressant agents and mass-flow rates.

SUPPRESSANT	TIME TO EXTINCTION (seconds)	AMOUNT OF SUPPRESSANT (grams)
(1.0 g/s)		
Ultra-fine mist	8.1	8.1
N_2	10.6	10.6
CO_2	12.3	12.3
(0.2 g/s)		
Ultra-fine mist	35.2	7.0

Note: The standard deviation for the extinction time and suppressant amount for ultra-fine mist, N_2, and CO_2 tests at 1.0 g/s is 1.82, 1.76, and 1.92 respectively, while for the ultra-fine mist at 0.2 g/s is 1.75.



(a) (b)

Figure 4. A flame propagating downwardly a cotton rag, (a) soon after ignition and before the injection of a suppressant agent, and (b) suppressed by ultra-fine mist surrounding the rag and just prior to extinction (note the smoldering embers above the flame).

CONCLUSIONS

An experimental investigation on the effectiveness of various suppressant agents in spacecraft fires under normal-gravity conditions has been conducted. Ultra-fine water mist clouds (mean diameter of 8 μm) driven by air or by nitrogen (N_2) are compared to single-fluid agents such as CO_2 and pure N_2 to evaluate their performance to suppress and extinguish typical fires that may be encountered in spacecraft such as energized wires, electrical components on circuit boards, and cloth. The suppressants are injected into a chamber with similar dimensions to the Space Shuttle Mid-deck Locker at low (0.2 g/s), medium (1.0 g/s) and high (2.0 g/s) mass-flow rates. A highly obstructed path to the fire is provided by a large baffle located perpendicular to the agent stream, between the nozzle and the fire. Extinction time and amount of suppressant agent needed to put out the flames are measured and used in the comparative study, along with other performance variables related to practical aspects of fighting fires under spacecraft conditions.

On a mass-basis comparison, ultra-fine mist is found to be more effective than CO_2 and N_2, with the exception of the burning-wire scenario with a high preheating power. In this case, ultra-fine mist is used to not only extinguish the fire, but also to cool the hot copper wire. This fact, in conjunction with the "small-fire syndrome" characteristic of water-mist suppressed fires, results in longer extinction times for ultra-fine mist, as compared to gaseous agents. Although at first the longer extinction times and additional mass of agent may appear as a disadvantage of water mist against CO_2 or N_2, the cooling effect of the water mist has the advantage of preventing the rupture of the wire, as it occurs when CO_2 and N_2 are applied at low mass-flow rates. This cooling effect may be essential to avoid disrupting the operation of critical equipment onboard the spacecraft while the fire is being suppressed. If shorter extinction times are desired, ultra-fine mist driven by N_2 can be used to combine the unique suppression properties of water mist in conjunction with the oxygen-depletion attributes of N_2. It is observed that the use of this mixed-agent suppressant results in a superior combination with excellent performance.

Ultra-fine mist is also effective on reducing smoldering extinction times with cloth fires by adding moisture to the burning rag and preventing the blowing of hot smoldering embers that can cause ignition of neighboring material in a tightly packed spacecraft under low-gravity conditions. In addition, the low-momentum injection of water mist may prevent the strengthening of the weak-burning low-gravity fires by reducing the convective currents, which are observed with the gaseous agents injected at high flow rates. Finally, the low momentum and *pseudo-gas* properties of ultra-fine mist with lower-than-10-μm droplets are also more effective than the high-momentum and larger droplet sizes generated by high-pressure water-mist sprays, which make water droplets incapable of moving around obstacles and reaching the fire [2].

These results point to ultra-fine water mist (or a combination of water mist driven by N_2) as a promising candidate to be used as agent in the next-generation spacecraft fire suppression system. The final selection of the optimum suppressant agent will depend on a detailed assessment of all the relevant design parameters and their relative importance for this unique application.

ACKNOWLEDGMENTS

This work is supported by the National Aeronautics and Space Administration, under Grant NNC04AA13A. The authors wish to acknowledge the invaluable help of Dr. Suleyman Gokoglu, the project monitor from NASA Glenn Research Center, and the technical help of the complete team at NanoMist™ Systems, Inc., who provided the ultra-fine mist unit for this study.

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