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NANOMIST– A BREAKTHROUGH WATER FOG TECHNOLOGY WITH PSEUDO GAS PERFORMANCE

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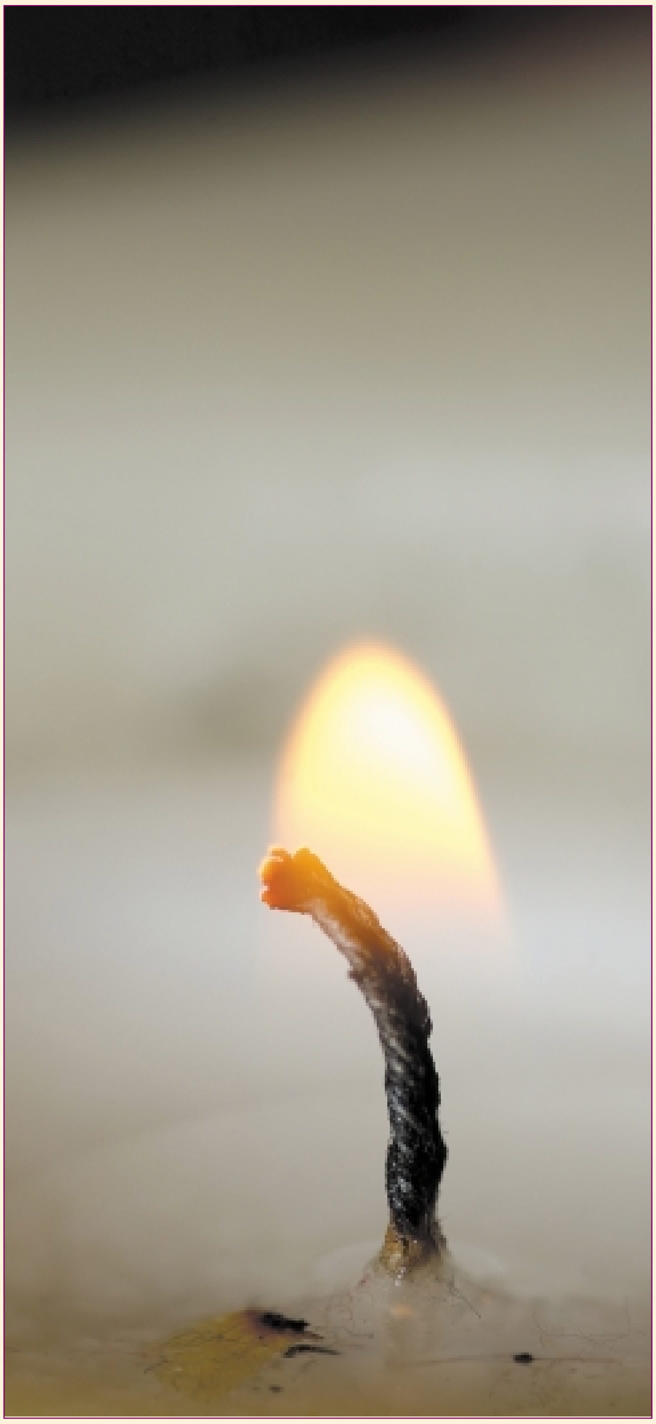
Dr. Adiga *is the founder and CEO of NanoMist Systems, LLC. His Ph.D. work was in the area of thermochemistry and combustion of solid rocket fuels. He has more than two decades of academic and industrial experience in the areas of combustion, explosions, fire science, materials processing, and innovative product technology. He is a member of the International Association of Fire Safety Science (IAFSS), the Combustion Institute, ASME-International, NFPA, and SFPE. He founded NanoMist Systems in 2001 with a vision of developing a new generation, ultra fine water fog technology by breaking up water droplets into pseudo gas or microfluids with tailored properties. He has been collaborating with the U.S. Naval Research Laboratory on both applied and technology evaluation of ultra-fine water mist for the past 3 years. He is also working with fire protection and materials industries on the high performance NanoMist ultra fine water mist applications.*



BACKGROUND AND TECHNOLOGY HIGHLIGHTS

A breakthrough in fire protection technology is evolving as a result of half a decade of basic and applied research, combined with technology evaluations and product development on a gas-like, ultra fine water fog in the form of a "microfluid" - NanoMist. This water fog microfluid, a dispersion of nearly micron-sized droplets in air or inert gas, meets the environmental, operational and performance requirements for many fire protection applications in a manner superior to current Halon substitutes. Unlike Halon substitutes, it does not produce toxic by-products as a function of fire size and fire exposure time. This breakthrough in ultra fine fog technology with its gas-like flow behavior, overcomes the shortcomings of existing water mist systems such as large amounts of water needed for extinguishment, limited flow around obstacles to reach hidden fires, and collateral water damage, over a range of fire sizes.

Figure 1. A dense gas-like ultra fine water fog (NanoMist) dispersion in a room

NanoMist Systems, LLC started the basic research and development of ultra fine water mist technology in 2001. The company has patented both process and product technology for the production of ultra fine water mist under the trademark, NanoMist. Extensive in-house research has been conducted demonstrating the unique behavior of ultra fine water mist, including its gas-like transport behavior, its self-entrainment into the firebase, and its powerful cooling and inerting behavior derived from its rapid vaporization and the resultant oxygen displacement by the expanding steam.

NanoMist ultra fine fog at controlled momentum flows like a dense gaseous (pseudo gas) agent such as Halon or CO_2 but is not toxic and is safe to breathe. Unlike conventional water mist, it flows in convoluted spaces with obstacles and baffles; it can negotiate corners and penetrate non-line of sight spaces. Because of its ultra fine droplet size, the microfluid has extremely high aerosol stability, making it an excellent "inerting agent" to secure the space and prevent re-ignition, or reflash, after the fire is extinguished.

The photographs depict unique features of NanoMist such as dense gas-like dispersion and total flooding behavior (Figure 1), a highly stable dense fog on standby (Figure 2), and its ability to pass through convoluted channels with sharp corners (Figure 3). The stable microfluid can be an attractive agent in fuel tank inerting to help replace or relieve some of the burden on the OBIGGS (Onboard Inert Gas Generating System). In addition to mimicking Halon substitutes in transport behavior, water fog has a higher latent heat extraction capability, a key criteria in fire suppression efficiency. Based on cup burner extinction data reported by NRL researchers, NanoMist mass concentration has been shown to be 1.5 times more efficient compared to Halon 1301.

The technical rationale behind this pursuit of NanoMist ultra fine water mist is to provide an environmentally benign permanent alternative to Halon and Halon substitutes by mimicking the properties and efficiency of Halon and other clean gaseous agents in their transport and fire suppression behavior. The reasons for moving away from Halon and their substitutes cannot be overemphasized, based on the adverse effects of these agents to occupants and equipment when exposed to fires of varying sizes and exposure times. Various fire and explosion protection agencies and the fire protection community have strong preferences for water for their various applications to replace their current use of Halon and halogenated chemicals. There are several urgent reasons for the continued search for a "permanent" solution based on water. International end-users must comply with more severe regulations addressing environmental concerns including global warming, atmospheric lifetime constraints, and ozone depletion, which largely limit alternatives other than water. Moreover, hydrogen fluoride (HF) production due to the decomposition of common gaseous Halon alternatives in flames or hot regions poses significant corrosive and health concerns to occupants. Even on a performance level, the gaseous fluorocarbon-based Halon alternatives fielded over the years require 2-3 times (or more) capacity compared to Halon for equivalent protection, which creates weight and space issues in many applications.

Regular water mist systems (featuring 100-200 micron droplet diameters from high momentum jets) have some design challenges that have limited their implementation. These include: (1) large droplets have difficulty in flowing through cluttered areas, around corners and behind obstructions like a gas, (2) these inefficiencies result in the use of large amounts of water, leading to systems that are often too big and heavy even if they work satisfactorily, and (3) collateral damage and wetting that cause operational and environmental limitations for some applications, and considerable cleanup down time and expense. The NanoMist technology has overcome these shortcomings of regular water mist.

Figure 2. A pool of stable NanoMist ultra fine water fog stored for later use

Prior to NanoMist work, there were several concerns regarding ultra fine water mist technology applications to fire protection areas, based upon the limited knowledge then available. They include: 1) the notion that extremely fine mist may not survive fire radiation and may not make it to the fire because of pre-vaporization, 2) the low momentum of mist creates a transport problem – fine mist may not reach the fire base because of its inability to penetrate, and 3) a clear absence of a scalable process technology to produce such an extremely fine fog in large enough quantities to extinguish fires of a reasonable scale, with a sufficiently high mist concentration. After half a decade of research on NanoMist, it was discovered that the pre-vaporization of mist is not a significant problem since the background humidity established in the fog will reduce further vaporization. Although the self-entrainment of the mist to fire base has been designed successfully in some cases, the timely transport of ultra-fine mist to the firebase is still an issue, for which intense research is ongoing. The lack of scalable ultra fine mist technology was at last overcome, to some extent, by NanoMist technology by using robust modular units. Work continues on a next generation production device to accomplish seamless scaling of throughput without adversely affecting the mist quality. Based upon research and testing so far, ultra fine water fog should provide a "paradigm shift" in future fire protection technology by providing a water-based permanent solution to replace Halon and Halon substitutes.

NANOMIST PRODUCT TECHNOLOGY

NanoMist is a proprietary, ambient pressure, ultra fine water fog technology that produces extremely fine fog (below 10 micron), without the use of pressure systems or nozzles, that has very different physical characteristics from conventional water mist systems. The technology to produce ultra fine mist with high number density and extremely fine droplets with a controlled momentum is achieved by NanoMist technology through the use of ultrasonic generators and a patented internal flow process technology. As a result, the NanoMist ultra fine water fog thus created exhibits dramatic enhancements in its desirable properties as a pseudo gas over regular water mist techniques.

NanoMist prototype units with capacities of 250-500 ml/min are built using off-the-shelf electronics, mechanical and other electrical components. This device is now being miniaturized to a unit no bigger than 6 inches in diameter by six inches tall, via customization of devices and components already available in the marketplace. Higher flow capacity units are in development that will greatly expand the coverage area per unit and the rate at which the fog can quickly fill a large area. Efforts are underway to bring significant step changes in production rates by integrating different atomi-

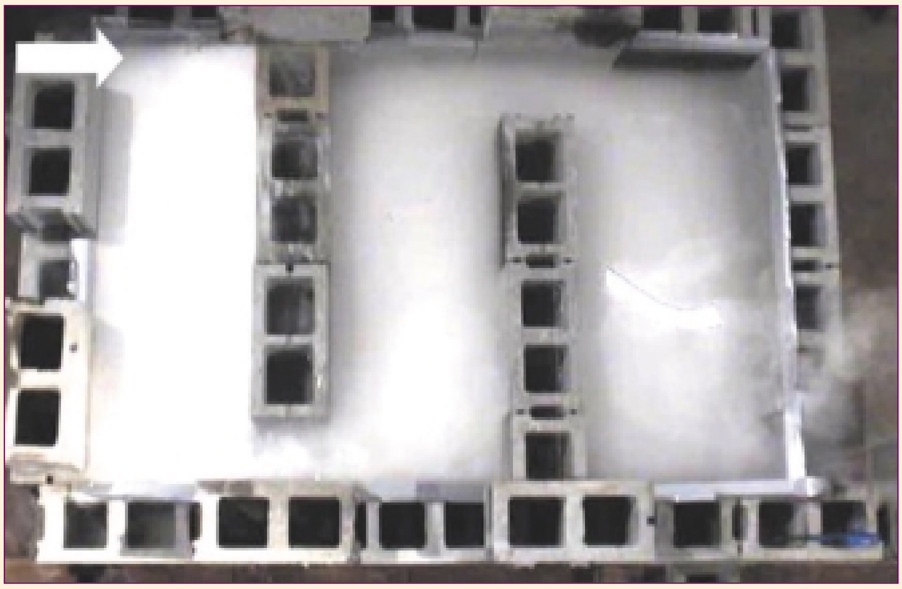


Figure 3. Gas-like NanoMist flow in a channel with sharp corners and staggered multiple baffles

zation methods without adversely affecting desirable NanoMist properties.

SOME DISTINGUISHING FEATURES OF NANOMIST PRODUCT TECHNOLOGY

NanoMist is not just one more water mist technology. The technology produces a unique microfluid with strikingly different features from current regular two-phase pressure- spray mist. A summary of salient features of this ultra fine fog technology is provided in the following paragraphs.

Ultra fine fog: Generally, NanoMist mean droplet size is less than 10 microns in diameter when it is produced and transported out under controlled conditions. The surface-to-volume ratio is several orders of magnitude higher for NanoMist as compared to regular mist (100-200 microns).

Mist mass loading: Unlike regular mist technology, NanoMist has a wide range of mist mass loading capability, providing more firefighting capability per unit size.

Low momentum: Unlike regular mist, NanoMist exit (or discharge) velocity can be finely controlled to mimic the local free convective flow field for special applications of fogging and inerting. In regular pressure-atomization, it is not easy to control the spray momentum without adversely affecting the spray characteristics.

Heat absorption capacity: NanoMist absorbs ~ 2.5 million joules/kg of heat. While the regular spray mist absorbs the same amount of heat per unit mass, the ability of micron-sized NanoMist droplets to absorb energy quickly makes it a superior cooling agent. This gives far greater heat extraction rate capability per unit volume compared to conventional mists per unit time, due to a faster evaporation rate.

Aerosol stability: Unlike regular mist, NanoMist is highly stable because of micron-sized fine droplets and the hyper-humidity created initially by fast vaporizing micro droplets, which hinders additional droplet vaporization. This is important in total flooding and inerting applications, as droplets remain in the air for a sufficient time so that re-ignition can be prevented.

Gas-like transport behavior: Mist behavior resembles a gaseous species at low velocity. Diffusion seems to play a major role in low velocity fogging scenarios. NanoMist can flow like a gas and pass over obstacles, baffles, and tube bundles and easily negotiate corners (including 180 degree turns).

Self-entrainment behavior: Because of its microfluid character, NanoMist can hang around like a "stagnant" gaseous pool. Thus, NanoMist can be fluid-dynamically positioned around a firebase so that the fire will "self-entrain" it like air. This self-inflicted fire extinction is a novel concept that evolved from NanoMist studies during the last 3-4 years.

NanoMist as a cooling and inerting agent for post-fire treatment: NanoMist can be deployed as an inerting agent after a fire has been knocked down by another agent to secure and prevent re-ignition or reflash. Because of its extreme aerosol stability and quick heat absorption behaviors, NanoMist can hang above a fuel spill or hot fuel for an extended amount

of time. By discharging NanoMist along with fire suppression agents or after the fire has been knocked down, NanoMist can form a heat-absorbing cloud above the fuel surface and prevent re-ignition or re-initiation of fire by a subsequent ignition threat, and continue to be re-supplied, even in ventilated spaces, to provide extended inerting protection as long as desired. It is a powerful cooling medium under optimized flow conditions. This is a unique behavior not exhibited by regular water mist.

Non-wetting "dry" mist: Because of its fine droplet size, the mist does not really wet the surface since it vaporizes quickly. This behavior has been exploited in our patent (issued) on electronic cooling. In addition, the U.S. Navy evaluation of NanoMist for electronics space (data center) fire protection clearly indicated cable modem survivability during NanoMist flooding tests inside a sub-floor. Not only can electronics continue to operate when exposed to NanoMist (when needed for critical applications), but water damage in general is not experienced, which is particularly important when considering an agent for areas sensitive to collateral damage from water.

Environmentally benign permanent solution: NanoMist water mist is an environmentally benign suppression agent that provides a permanent solution to fire protection systems, with other benefits consistent with other water-based products, including the lack of hydrogen fluoride generation.

Ability to transport in ductwork: Its ability to be transported through small ductwork up to one hundred feet in length has been shown recently, which permits its generation and subsequent transport from a centralized production location in a multiplexed fashion, thereby eliminating the need for separate independent NanoMist units for each location.

THE ROADMAP OF NANOMIST TECHNOLOGY EVALUATION

In early 2003, the Navy Technology Center for Safety and Survivability (NTCSS) of the U.S. Naval Research Laboratory (NRL) conducted NanoMist technology evaluations via CFD modeling and total flooding tests [1,2]. This was followed by a technology evaluation of NanoMist for electronics space fire protection for next generation DDX shipboard applications as a part of the Future Naval Capability (FNC) under the Office of Naval Research (ONR) program. The tests were conducted at Hughes Associates, Inc. This and other research showed that NanoMist behaved like a gaseous agent, both in terms of flowing through convoluted spaces with baffles and extinguishing telltale and cable fires [3]. Following this evaluation, extensive basic research including CFD modeling was conducted in-house as well as by the U.S. Naval Research Laboratory [3-6]. The gas-like transport behavior and ability to extinguish cable and other Class A fires in a Space Shuttle mid-deck locker box mockup with flow obstructions was demonstrated by the Center for Commercial Applications of Combustion in Space (CCACS) at the Colorado School of Mines in their NASA funded project [7]. Beyond these studies, key players in the commercial fire protection industry have taken notice of this new technology and are starting to view this technology as an alternate to halon substitutes as well as chemical systems. This progress to date shows great promise to a wide range of applications throughout various segments of the fire protection industry in the very near future.

Figure 4. The Navy electronics space fire protection tests conducted by Hughes Associates, Inc

NANOMIST FIRE PROTECTION TECHNOLOGY RESEARCH AND EVALUATIONS

NanoMist Electronics Space Fire Protection: As indicated above, the Navy-sponsored project at Hughes Associates, Inc. has evaluated the application of NanoMist in an electronics space mockup [3]. This technology evaluation was intended for shipboard applications. On the commercial side, this application relates to data center fire protection where Halon substitutes are currently used. NanoMist was the only water mist system that was able to extinguish all of the test fires without the aid of a complementary nitrogen system. The addition of flow and surface area obstructions, and the removal of some of the floor tiles allowing mist leakage did not result in a corresponding significant increase in the system requirements to cause extinguishment of the telltale fires (Figure 4). The mist requirement corresponding to extinguishment of a cable bundle fire was 21% less than those corresponding to extinguishment of the telltale fires, implying an additional margin of safety with reference to actual sub-floor installations where electrical cables represent the majority of the fuel load. The electronics exposure test to water mist did not show a significant impact on the ability of the electronics, when installed in a manner consistent with industry practice, to continue operating during exposure. An exposed modem was able to continue operating throughout the 10-minute exposures while housed inside the simulated electronics cabinet.

U.S. Navy Evaluation of Ultra Fine Water Mist: Significant basic research work has been conducted for the last four years by the U.S. Naval Research Laboratory on the characterization of ultra fine water mist, cup burner tests, and fire suppression behaviors [5,6]. The work included both computational and experimental studies on PMMA (Poly Methyl Methacrylate) slabs and cable bundle fire suppression using NanoMist as well as regular nozzle-based water mist technologies. For the most part, NanoMist has been found to be more efficient in extinguishing and controlling the fire growth compared to regular water mist. Some photographs, taken from their published work, of fires in wind tunnel tests are shown in Figure 5.

Colorado School of Mines (CSM) Tests in Space Shuttle Mid-deck Locker Box Mockup: The CSM group has conducted considerable work on fire suppression behavior in their Space Shuttle Mid-deck Locker box mockup [9]. They have compared NanoMist flow and fire suppression behaviors with regular pressure-spray water mists. NanoMist performed like gaseous agents in passing through baffles and extinguishing the cable fire behind the baffles. This was superior to regular mists, which could not pass the baffles easily. Some photographs of their published work are shown in Figure 6.

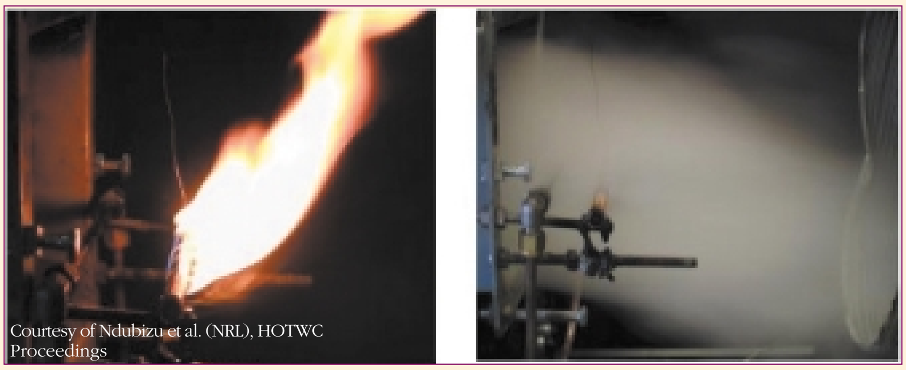


Figure 5. Boundary layer flame studies in NRL wind tunnel using NanoMist as well as other water mist

Figure 6. Colorado School of Mines work on Space Shuttle Mid-deck Locker box mockup study

Figure 7. *Restaurant kitchen deep fat fryer fire extinguishment by NanoMist*

NanoMist Commercial Kitchen Fire Protection: Restaurant and commercial kitchen cooking oil fires pose a unique challenge to fire protection systems. With large heat releases and large flame fronts, the initial fires pose a major threat. The reduced flash point of the burnt oil poses an additional challenge of a lingering re-flash threat until the oil is sufficiently cooled. Current restaurant and commercial kitchen cooking oil fires in deep fat fryers use wet chemical agents to knock down the flame and then either use a chemical foam blanket or a water spray to prevent reflash. In each case, there are hazards associated with this approach to preventing reflash. Foam blankets insulate the oil surface, retarding the cooling rate, and extending the re-flash threat. The use of regular water mist over deep fat fryers normally results in a violent fireball effect. NanoMist ultra fine water mist fire tests were conducted at the NanoMist Fire Laboratory following the UL300 protocol. The water required (based on the application rate of about 1000 ml/min) to extinguish the fire was below 200 ml. The ultra fine mist knocks down the fire "quietly" without leaving any moisture behind. The photographs (Figure 7) of the fire and post-fire scenarios are shown below.

The unique self-entraining behavior of NanoMist ultra fine water mist surrounding a pool fire is shown in Figure 8, where a near-free convective mist cloud suddenly surrounds the firebase. The situation of submerging the liquid pool fire in mist is not easy to reproduce by regular streaming pressurized water spray technology.

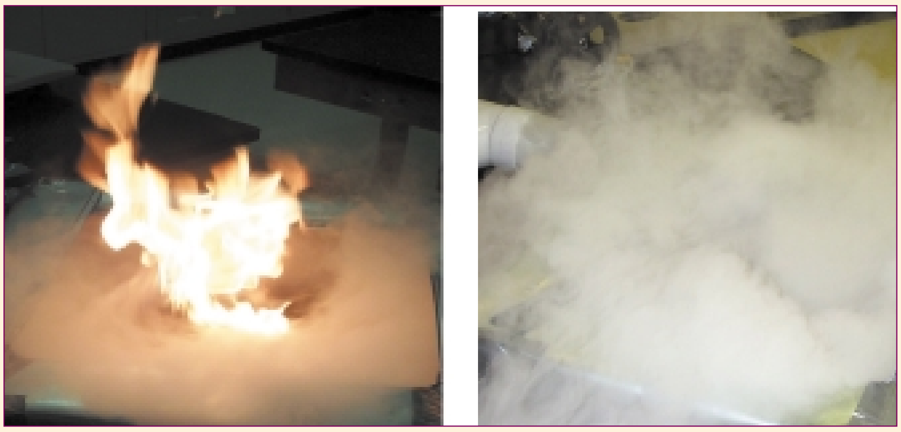


Figure 8. *A special configuration of heptane liquid pool fire suppression where NanoMist surrounds the firebase*

AVIATION SAFETY AND SURVIVABILITY APPLICATIONS

NanoMist devices have been designed for generating fogs of jet fuel to create fuel-rich conditions within the ullage of a fuel tank to inert against explosions. This concept of inerting or quenching by use of fuel was used in actual fielded military aircraft in the 1950s by injecting pentane fuel onto fuel tank explosions as they were occurring, and was understood then to be a weight-efficient means of explosion suppression; only the limitations of fast response detection at the time limited its proliferation to other platforms. Published research conducted decades ago by McDonnell Douglas found that the concept of pre-inerting an ullage by spraying it with a fuel mist was an effective means of inerting. However, their protection regime was only observed over a limited temperature range due to the limits of high-pressure nozzles that could achieve only a 13% weight of fuel in air, rather than the 22% required for all conditions. Notably, NanoMist can provide over 30% by weight of fuel in air, which is more than adequate for the task. Figure 9 shows that a kerosene fuel fog can create opaque, well mixed fog conditions that can reside for extended periods, whether or not the fog is replenished. This simple system (using fuel or other inerting agents, including water),

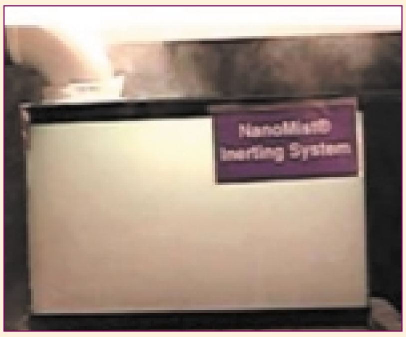


Figure 9. *Tank filled with ultra fine kerosene fog*

which can be mounted adjacent to or in a fuel tank, is a low cost, lightweight and easy-to-retrofit option with many advantages over OBIGGS, and may also be more practical for applications like UAVs and small aircraft.

Such systems using water or other inerting agents can also protect cargo or large dry bays, either as a stand-alone system or by providing sustained re-ignition protection after initial fire knockdown from a fast-response system. It can also provide crew protection in a safe manner against fire events. These capabilities can also be used in the engine and crew compartments of armored and other military ground vehicles to provide sustained re-ignition prevention, and even surrounding the exterior of some vehicles to provide sustained inerting of spilled fuel pools under such damaged vehicles until occupants can be evacuated from the disabled vehicle.

Most of the research and development work and technology evaluation described above are available in HOTWC proceedings, NFPA conference proceedings, SPFE conference, Fire Safety Journal, and other Combustion and Fire safety journals, NRL Memorandum Reports and Letter Reports.

CONCLUDING REMARKS

Ultra fine gas-like water fog is a viable alternate to Halon and other clean gas agents and provides an environmentally benign permanent solution. The basic research and technology evaluations to date indicate good progress in terms of meeting these demands in some selected fire scenarios until seamless scaling and transport issues are resolved. Therefore, in our continued search for alternatives to Halon and other chemical agents, ultra fine water mist seems to be positioned well to take the "heat", and extinguish fire and assure safety long after the fire is gone by cooling and inerting. It certainly has the potential to replace Halon substitutes in selected fire protection areas, including commercial, military, maritime, and aerospace fire scenarios. Unlike other gaseous agents, the ultra fine fog technology embodied in NanoMist provides both fast primary fire knockdown capability as well as sustained post-fire securing by cooling and inerting.

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