Fine Water Mists for Suppression of Class B Fuel Fires

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Introduction

The use of halons as fire suppression agents is being phased out in the industrialized world as a result of international ratification of the Montreal Protocol. **An** extensive search is now under way to identify replacement agents that are environmentally compatible and effective fire suppressants. As part of this search, the US Air Force funded a Small Business Innovations Research contract with ADA Technologies, Inc. to investigate the ability of fine water mists as an agent in the suppression of Class B fuel fires.

The project explored the effects of several properties of a fine mist fire suppression system on its ability to extinguish Class B fuel fires of two different sizes. The properties were the ***size of droplets*** generated by the fine mist nozzles in the system, the ***flow rate of water*** supplied to the nozzles, and the *style of nozzle.* Dual-fluid atomizers that used a flow of compressed air to assist in droplet formation were tested along with hydraulic nozzles which employ water pressure alone to supply the energy for generation of fine mist droplets.

A simple model of the combustion of hydrocarbon fuels was used to select a baseline water flow for a fine mist fire suppression system. A test fixture was fitted with instrumentation to measure temperatures and to sense the presence of flames, so that the performance of candidate fine water mist fire suppression configurations could be evaluated. **A** test matrix was prepared to investigate the effects of average mist droplet size and water flow rate on the relative performance of the fine mist configurations.

The primary objective was to determine the droplet size and water flowrate that is most efficient in extinguishing small and large fires in a test chamber. **A** secondary objective was to establish atomizer performance requirements for further development and optimization of fine water mist fire suppression systems for specific fire scenarios.

Nozzle Selection

In order to create droplets in a spray, energy must be supplied to the liquid to overcome the surface tension forces [Lefebvre, 1989]. For small droplets, the amount of energy required becomes significant. Several mechanisms have been used in spray nozzles to supply this energy, including high pressurization of the liquid, kinetic energy supplied as velocity, ultrasonic energy, and energy from compressed air supplied to a nozzle simultaneously with the liquid. For high pressure hydraulic nozzles, the designs typically use fine orifices to maintain backpressure on the liquid supply, and are therefore subject to clogging, especially when operated intermittently. Kinetic energy sprays are generated with spinning disk-type atomizers, which again do not lend themselves easily to intermittent operation. Ultrasonic energy does not couple efficiently into a liquid stream, and therefore is practical only for low flow applications.

Two-fluid atomizers typically inject a liquid jet into a gas stream flowing at a higher velocity, so that the liquid is sheared by the gas to break the jet into small droplets. There is much room in this concept for design features in a particular nozzle that optimize the efficiency at which energy is removed from the gas stream to overcome the liquid surface tension and promote formation of small droplets. In some designs, the liquid is broken into large droplets in a simple mechanical process, then the large droplets are subjected to the gas shearing action to further break them into small droplets. Other designs use multiple small jets to limit the dimension of water droplets formed in the nozzle.

The resultant flow from a two-fluid atomizing nozzle is a population of droplets that is carried into the surrounding environment by the atomizing gas. This is important for fire suppression applications, where this gas stream can help carry the fine droplets closer to the flames. The fine droplets have virtually no momentum because each has very little mass. Without the atomizing gas, there is a tendency for the droplets to follow the air motion created by the buoyancy of the combustion process; this buoyant plume usually rises upward from the combustion at the source of the heat.

Both two-fluid atomizers and hydraulic nozzles were selected for use in the fine mist fire suppression tests. Different models of each style were needed to obtain the range of droplet sizes specified in the test plan. The number of tests performed with each of the candidate nozzles was a function of the test results with that nozzle. When a test configuration was found to perform well, its limitations were explored by changing parameters such as fire location relative to the nozzle and water flowrates. If there was little relative merit to a test configuration, it was modified to improve the performance, or abandoned. The test matrix was designed to be flexible in that the early results dictated the selection of successive tests in the series.

Test Fixture

The fine mist fire suppression tests were conducted in a special chamber, modified to safely run the tests. The chamber is a pressure vessel initially designed to test pyrotechnics at simulated altitudes of up to 100,000 ft. The chamber is two meters in diameter, and about two meters long, with a total volume of about 6 m^3 (200 ft^3). Its axis of symmetry is horizontal, and it is equipped with a hinged cap on one end, which served as a door for easy access. The floor of the chamber is an expanded metal grate, which permits easy set-up of internal test components. There are numerous access ports through which water and air were routed to supply the fine mist fire suppression nozzles. A viewport on the cap opposite the door was removed, and the opening was used to run cables for the thermocouples and flame sensors, to supply circulation air to the chamber during fire tests, and to provide a location from which a video camera could document the testing. **A** schematic of the test chamber is shown in Figure **1.**

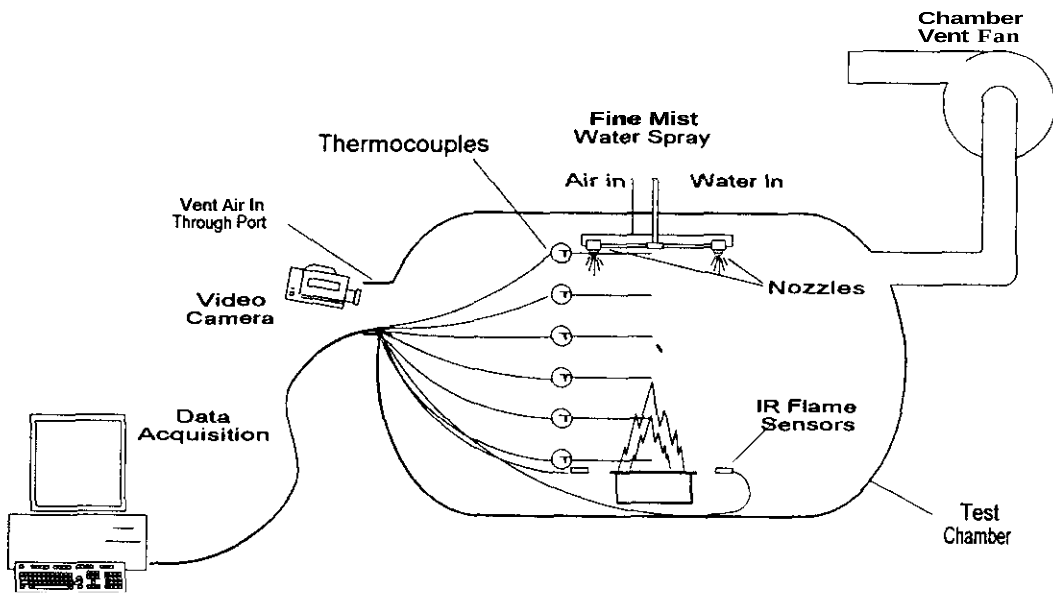

Figure **1. Test** Chamber Schematic

A vent fan ducted to the chamber was run during all tests to provide a constant flow of fresh air to the test fires. **As** a demonstration, a heptane fire was allowed to bum in the chamber for about 7 minutes to show that there was insufficient dilution of oxygen during a tire to affect the results of the testing.

N-heptane was used as the combustible liquid in the test series. The fuel was placed in a square pan of 9 cm **(3.5** in) depth for testing. Water was poured into the test pan to a depth of **5** cm **(2** in), with **2.5** cm (1 in) n-heptane added to float on the water. Three different *sizes* of pan were built for use in the test series, 7.5 cm, **11.4** cm, and 22.9 cm **(3, 4.5,** and **9** inches, respectively) on **a** side. The **22.9** cm pan represented an area that was nine times the smallest, so that "small" and "large" fires could be included in the test matrix.

The fire pans were also equipped with an expanded metal grate which was positioned about **2.5** cm (1 in) above the surface of the n-heptane fuel. This grate **served** as a heat source that could re-ignite the fuel if there was insufficient cooling from the mist nozzles during extinguishment of the fire. "Reflash" from adjacent hot surfaces is a common problem in fuel fires, especially if they are suppressed with techniques that do not provide much cooling. Reflash has been shown to be a problem with some halon extinguishing systems, so that the grates were included in the test matrix to determine the potential for reflash with fine mist fire suppression systems.

A total of six thermocouples were used in the chamber to measure temperatures during the test events. Theses were located at the surface of the fire pan and at regular distances from the surface to the level of the water mist nozzles at the ceiling of the test chamber. Air temperatures were measured at distances of 30 cm, 60 cm, and 90 cm (1, 2, and 3 ft) above the n-heptane surface. Other thermocouples measured the flame temperature immediately above the liquid surface, and the temperature of the grate. The last thermocouple was used to monitor the temperature of the n-heptane fuel.

Two other sensors were used to verify the extinction of fires with the fine mist. These units each consisted of a photodiode sensitive in the infrared region of the spectrum that was located just above the surface of the n-heptane, so that any flame present in the fire pan was detected. The photodiodes were checked in the laboratory, and found to have a detection range of from 4.5 to 22.5 cm (3 to **9** in). They were installed a few cm off the edge of the fire pan, on two adjacent sides to provide orthogonal coverage of the test events. ADA engineers designed and built a simple circuit to power the diodes and provide an output signal to the data acquisition system.

A personal computer was equipped with a data acquisition board and associated software to control the test sequence and collect and store data from the thermocouples and IR sensors in the test chamber. The system provided timing to control the ignition of the test fire, operation of the solenoid valves to supply mist to the fire, and logging of instrumentation to computer storage. All thermocouples and IR sensor data was recorded, and later downloaded to floppy disk for further analysis. **A** video camcorder was positioned *to* document all test events in the chamber; a video monitor was positioned near the data acquisition station to enhance the test engineer's ability to view the test in real time.

A series of checkout tests were performed to finalize a standard test procedure. A delay of 30 seconds between ignition of the fuel fire and actuation of the supply valves for the fine mist suppression system was selected to allow the test fire to fully develop. The data acquisition software was configured to measure the time from valve actuation to fire extinguishment as measured by the IR sensors.

Experiment Matrix

The proposed test matrix included 40 tests, and was designed to investigate the effects of four variables on the ability of fine mists to extinguish Class B fuel fires: fine mist nozzle type, mist droplet diameter, water flowrate, and size of the fuel fire. As the testing unfolded, we were able to perform about twice as many tests as planned, and to the list of variables was added the gas used in the two-fluid atomization nozzles. A summary table of the test variables and the associated numbers of tests is presented in Table 1.

The overall goal of the test matrix was to identify fine mist system parameters that provide the most effective fire suppression performance. The approach was to install a specific configuration and conduct a few tests to determine its ability to handle the test fire. If the configuration performed well, then changes would be made to determine how far from the baseline the performance was maintained. For example, could water flowrate be reduced and the fire still extinguished in the same amount of time? If the configuration was not particularly effective, some modification would be implemented and additional testing done to evaluate the change.

The net result of this approach was that the overall test matrix was driven by test results, rather than preplanned. Testing of specified nozzles and flows was included to ensure that the overall range of variables was covered in the matrix, but tests were added as needed to determine the limits of fine mist fire suppression for the standard fuel fire scenario.

Table 1. Fine Mist Test Configurations

Test Parameter	Configuration/Value	No. of Tests
Nozzle Style	Dual-fluid Atomizer	45
	Hydraulic Nozzle	40
Nominal Water Flowrate	$<$ 0.4 gpm	5
	0.5-0.9 gpm	17
	1 gpm (baseline)	52
	$>$ 1 gpm	11
Atomization Gas	Air	38
	N_2	4
	CO_2	3
Nominal Droplet Size	40 μm	41
	80 μm	32
	60 μm	4
	90 μm	4
	150 μm	4
Fire Pan Size	3 in. square	2
	4.5 in square	14
	9 in square	69

Test Results

A total of 85 tests were completed in the fire test fixture. Five parameters were investigated in detail, and a few tests were run at the end of the series to explore the impact of a fire suppression additive in the water mist. The parameters are noted in Table 1, and in the main are associated with the generation and delivery of fine mist droplets to the test fire. One other element of the test configuration was varied in the testing, the position of the mist nozzle(s) relative to the n-heptane fire pan.

The standard approach was to begin with a configuration of interest, and perform several tests at the baseline conditions. The results of these initial tests were reviewed, and additional tests in the matrix were defined to investigate the limits of performance for the current configuration. For example, if the initial test fires were extinguished quickly and consistently, the succeeding tests were run at reduced mist flowrates to determine the minimum mist injection rate at which fires could be successfully extinguished. Duplicate tests were run on selected configurations to establish the consistency of test results.

The primary parameter for evaluation of the fine mist configurations tested in the facility was the time required to extinguish the test fire. Of the **85** tests completed, the fine mist did not extinguish the test fire in **18.** To establish a baseline against which to evaluate the test matrix variables, we averaged the time required to extinguish for those tests in which the fire was put out. This was found to be just over **12** seconds.

In order to present an overall perspective on the test results, a table was prepared that grouped the required extinguishment times below and above the test series average. These data are shown in Table **2.** The **85** tests have been divided into six ranges of time to extinguishment, three less than the average time and three greater than the average. It it noteworthy that although the mean time was **12** seconds, the median was much lower, just under six seconds. In fact, almost a third of the successful tests (where the fine mist extinguished the test fire) were put out in three seconds or less, and over **80%** were successfully extinguished in less than **12** seconds. In **18** tests we were unable to extinguish the test fire. These cases were primarily when water flows to the nozzles were reduced well below the baseline one gallon per minute value, or when the fire was located such that there was not adequate mist applied. This was usually a problem with the spray pattern of the nozzle under test, or a situation where the fine mist droplets did not penetrate the fire plume due to a lack of momentum.

Time **to** Extinguishment	**No. of** Tests	Fraction **of Successful** Tests(%)
12-20 sec	**9**	**13.4**
20-30 sec	**4**	**6.0**
Did Not Extinguish in **30** sec	**18**	**N/A**

Relative performance of the configurations under test in the series is presented in Figure **2. Here** the ***deviation*** from the overall average time is plotted for each test configuration on a single graph; bars that extend below the zero line represent tests where the fire was extinguished in ***less*** than the average time. Most configuration bars represent the average for several tests. Both dual-fluid atomizers and single fluid hydraulic nozzles are included. The configuration bars are shown from left to right in order of increasing droplet *size,* and increasing water flow rate within each droplet size. Each bar is labeled with a nozzle type code (D or *S)* and a water flowrate in gallons per minute.

Several trends are evident in the data shown in this Figure. The dual-fluid atomizers are much more effective at the smallest droplet size; the opposite is true for the single-fluid hydraulic nozzles. Water flowrate seemed to have a greater impact on time to extinguish for the single-fluid nozzles than for the dual-fluid atomizers. This was especially significant at flows below the baseline 1 **gpm,** where the single-fluid nozzles had difficulty in extinguishing the test fires. **In** fact, there were flowrates at both the 40 μm and 80 μm sizes where the single-fluid nozzles did not put out the test fire (indicated by large "X" in the bar).

On the other hand, the single-fluid nozzles were very effective at droplet sizes near or above 100 μm. This is believed to be a result of the increased momentum of these larger droplets, which improved their ability to penetrate the turbulence generated by the heat release of the fire. These larger droplets are able to reach the fuel surface, where they cool the combustion reaction and dilute the oxygen being delivered to the tire.

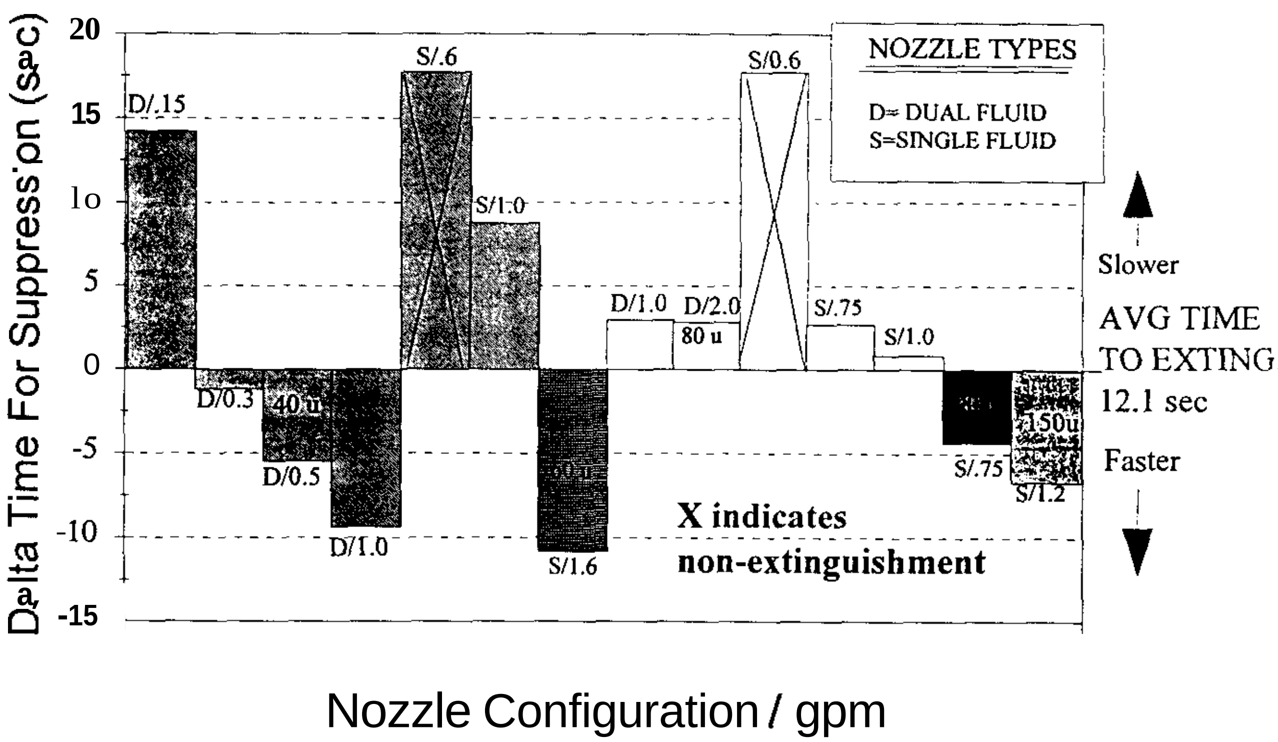

Figure 2. Relative Performance of Fine Mist **Systems**

Figure **3** presents a more detailed **look** at the results for the 40 μm droplet diameter. The dual-fluid atomizer at the baseline flow of one **gpm** performed extremely **well, with** an average time to extinguishment of less than **3** seconds. Reducing the flow rate **by** a factor of two increased the extinguishment time to less than seven seconds. **A** further reduction in flow rate to 0.3 gpm through the atomizers caused another increase in the average time to extinguishment, which remained below the average for all tests. Only when the water flow rate was reduced to 0.15 gpm did the average time to extinguishment for the dual-fluid atomizer at 40 μm droplet diameter rise above the all-test average. For this low-flow condition, one of the two tests was unsuccessful; it appeared that this flowrate was below the minimum required for consistent extinguishment of a Class B fuel fire with dual-fluid atomizer.

The single fluid nozzles showed relatively poor performance at the 40 μm droplet diameter. The test fires were successfully extinguished at a water flow rate of one gpm, but the required time averaged about 20 seconds. When the water flow rate was dropped to 0.6 gpm, the fine mist from the single-fluid nozzle was unable to extinguish the test fire. Additional tests were run with a dilute additive at a water flow rate of 0.75 gpm, but these were unsuccessful as well.

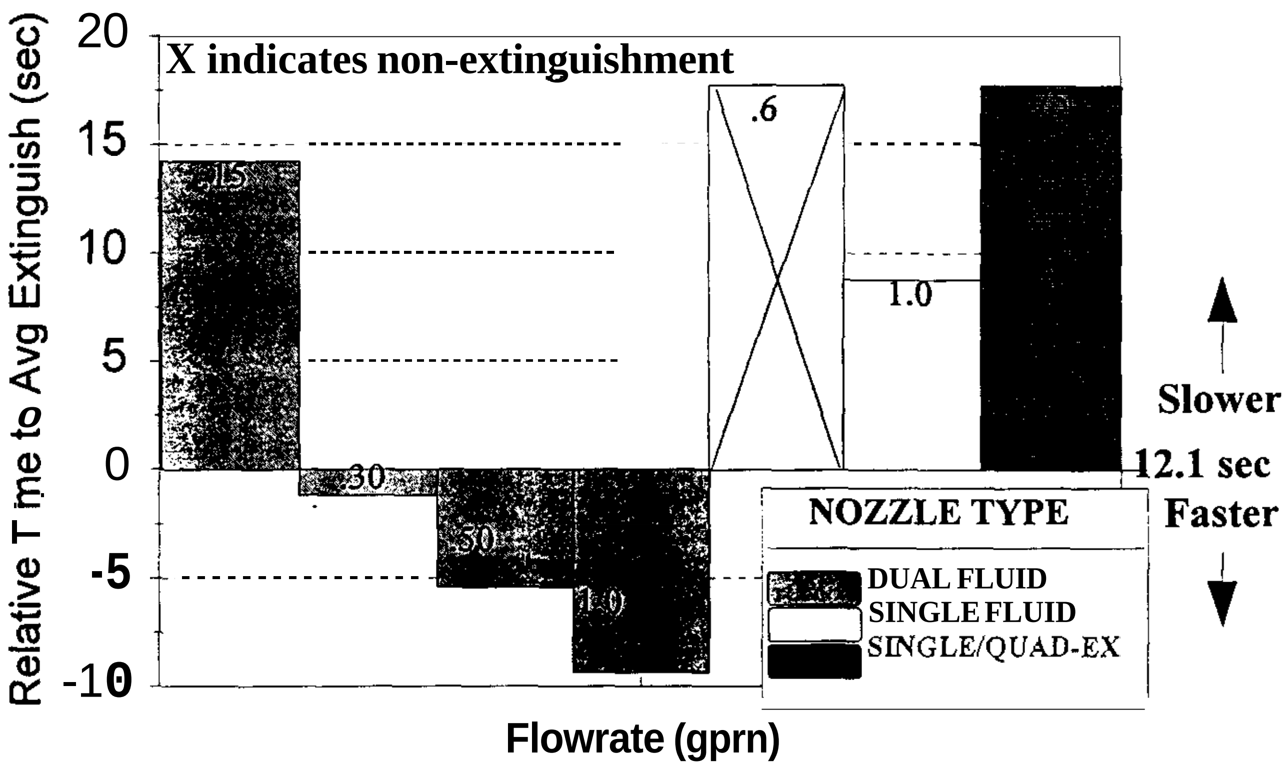

Figure 3. Performance of Fine Mist Systems with 40 μm Droplets

A very different result is seen for the 80 μm nominal droplet diameter data in Figure 4. In general, the larger droplets took longer to extinguish the test fues. For all the configurations tested, the average times to extinguish the fires were greater than the 12.1 second average. Here the dual-fluid atomizer showed performance that was worse than the single-fluid nozzles; further, there was no discernable difference when the flow rate was doubled. Tests with the single-fluid nozzle at the baseline one gpm flow rate resulted in extinguishment in an average time just greater than the overall average. As the flowrate was decreased, a trend toward increasing time to extinguish was observed. In fact, at 0.6 gpm, the single-fluid nozzles were unable to extinguish the test fires. Additional tests performed with a dilute additive showed a slight reduction in time to extinguish at the baseline one gpm flow rate.

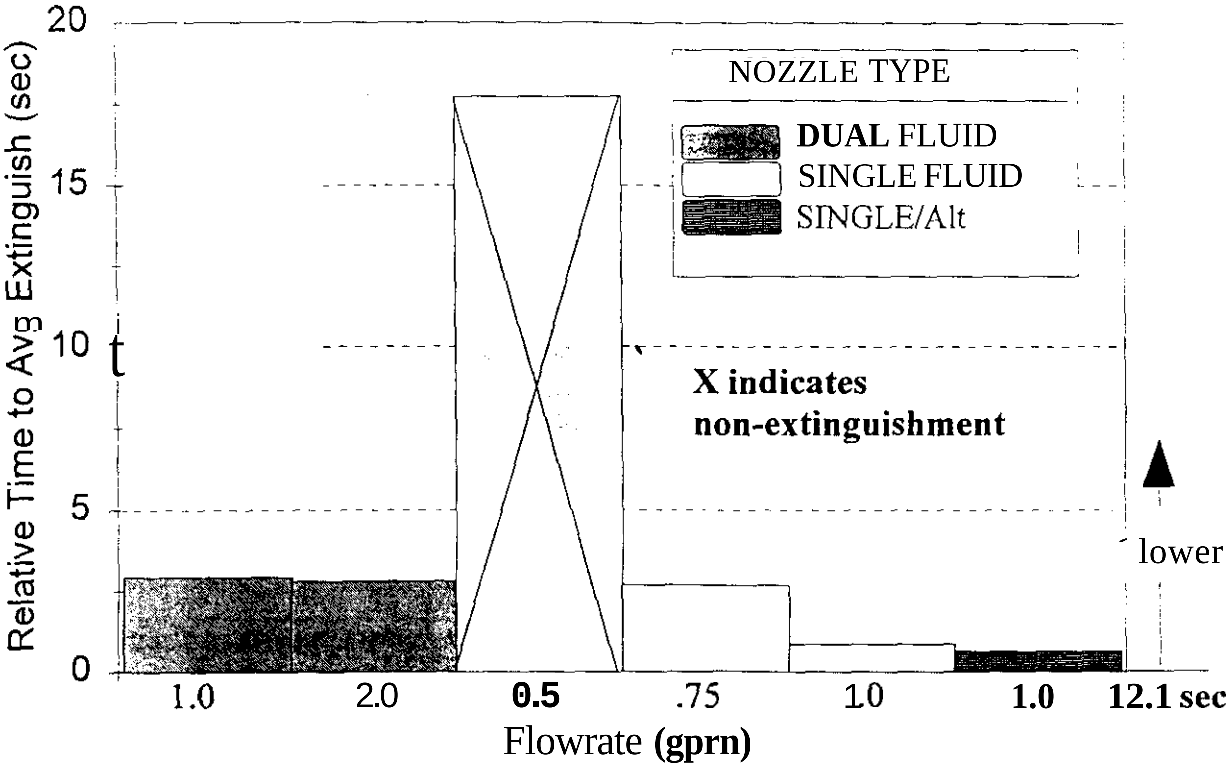

Figure **4.** Performance **of** Fine Mist Systems with **80** μm Droplets

One other test parameter was investigated in the test matrix: the location of the fire relative to the mist nozzle(s). Two modifications were made to the baseline configuration in these tests. For several of the dual-fluid tests, the fire was moved horizontally relative to the single nozzle installed in the chamber. For several of the single-fluid tests, the test fire was elevated to bring it closer to the nozzle discharge.

The dual-fluid atomizer was able to successfully extinguish the test fires when they were moved horizontally 30 cm (12 inches) upstream or downstream of the atomizer. Here "upstream" and "downstream" refer to the combustion air supplied to the test fire from a port in one end of the chamber. This air flowed past the fire and mist atomizer to an exhaust port on the far side of the chamber. At **45** cm (18 inches) difference between the edge of the fire and the atomizer, the fine mist was beyond its range; two of three tests were not extinguished.

In a few single-fluid nozzle tests, the fire was elevated **30** cm (12 inches) above its baseline location to bring it closer to the *mist* nozzle. This was done for the 40 μm droplet tests, where the fine droplets appeared to have difficulty in penetrating the fire plume to cool the combustion. Bringing the fire nearer to the nozzle had a positive impact on the performance of the fine mist, so that fires that previously were not extinguished could be successfully put out. However, this improvement did not extend to tests where the water flow rate was decreased below the baseline one gpm level.

Conclusions

The conclusions for this test program are divided into general observations on the performance of fine mist systems, and more specific discussions of the parameters investigated in the test series.

Overall, the fine mist fire suppression configurations tested were very successful in extinguishing Class B fuel fires. The single most significant element in quickly extinguishing the test fires was getting the mist to the fire. This was seen in the dual-fluid atomizer as sufficient air velocity from the atomizer to carry the small droplets into the fire plume to the source of combustion. For the single-fluid nozzles, the issue was expressed as sufficient droplet size and total water flow to create a droplet concentration and momentum to penetrate the plume. This is why the droplet size performance was so dramatically different for the two styles of nozzles.

Dual-fluid atomizer

The dual-fluid atomizer was very effective against the Class B fuel fires. The atomizer(s) would fill the chamber quickly with a fine fog that was seen to persist much longer than the single fluid nozzle droplets, in part because of the diffusion and mixing that was promoted by the atomization gas injected into the protected space. Specific observations include:

- The compressed air flowing from the dual-fluid atomizer carried the small water droplets into the combustion zone in sufficient quantity to very effectively extinguish the test fires.
- The 40 μm droplet size was shown to be much more effective than the 80 μm size; this is most likely an effect of the increased surface area per unit volume for the smaller droplets.
- A few tests run with inert atomization gas (CO_2 and N_2) showed reduced extinguishment times; the dilution of oxygen with the inert gas complemented the effectiveness of the fine mist.
- Horizontal displacement of the test fire up to 30 cm (12 inches) relative to the atomizer did not alter ability to extinguish fires.
- No reflash was observed, although the extinguishment times for cases with the reflash mesh were slightly longer.

Single-fluid nozzle

The single-fluid nozzles were effective extinguishing fires when the droplet size was larger than that for the most efficient dual-fluid atomizers. This is attributed to a requirement for added mass in a typical droplet to penetrate the combustion zone; the only means to impart momentum for the single-fluid nozzle design is from the exit velocity of the droplets from the nozzle. For the single-fluid nozzles, the larger the droplet, the quicker the test fires were extinguished. Other observations for the single-fluid nozzle tests included:

- Higher water flow rates were more effective than lower flow rates. Flow rate seemed to dominate droplet size in its impact on fire suppression performance.
- No persistent fog was formed; the mist dissipated very quickly in the chamber after a test.
- There was less turbulence in the protected space with the single-fluid nozzles than when the dual-fluid atomizers were used. This meant that the fine mist droplets were mixed into the fire at a slower rate, increasing the time needed for extinguishment of test fires.
- Uniform coverage of fine mist in the test chamber was more difficult to achieve with the hollow cone spray nozzles used in the testing. (These have a spray distribution pattern that is an expanding annular ring, where there is a significant reduction in droplet density near the center of the pattern.) With only small changes in nozzle position relative to the test fire, the amount of mist impacting the combustion zone was reduced, and extinguishment of the fire was unsuccessful.
- The single-fluid nozzles required small orifices and high operating pressures to generate droplets less than 100 μm in diameter. These are susceptible to clogging if care is not taken in the water delivery system.

The advantages of single-fluid nozzles lie in the simplicity of the system compared to the dual-fluid atomizers. A system can be configured with a multinozzle heads that operate at relatively low pressure (around 100 psig). Several nozzles are installed on facets of a single head, so that the combined flow generates uniform coverage for the protected area. The multiple nozzles afford extended coverage from a single head. The single-fluid design requires only a water supply line, and is therefore quicker and less expensive to install. In addition, since the water supply can be plumbed into the domestic water feed, run time for a single-fluid system is virtually unlimited. This is definitely not the case for a system where atomization gas is needed to generate the fine mist droplets.

Effect of droplet size

Modeling showed this parameter to be most significant in the rate of heat transfer from the fire to the mist droplets. This result is reflected in the very rapid extinguishment seen in tests where fine mists are effectively delivered to the combustion zone by atomization gas from dual-fluid atomizers. Conversely, when single-fluid nozzles were tested, larger droplets were generated and higher flowrates were needed before exinguishment times dropped below the overall test average. For this condition, the extinguishment mechanism wasn't the high rate of heat transfer in the small droplets, it was the total heat transfer from a multitude of somewhat larger diameter droplets.

The improved heat transfer rates available with the fine mist droplets are tempered by the difficulty in transporting them into the combustion zone of the fire. For this purpose, the dual-fluid atomizers were seen to be very effective. Single-fluid nozzles needed larger droplets to efficiently penetrate into the combustion zone. The performance of small-droplet nozzles was a strong function of their ability to efficiently and uniformly distribute the mist into the protected space.

Effect of water **flow** rate

The flow rate **of** water in the fine mist fire suppression configurations was a significant parameter in their ability to extinguish test fires. Higher flow rates **always** resulted in quicker extinguishment of the test fires. The minimum flow needed to consistently extinguish test fires was much greater for single-fluid nozzles than for dual-fluid atomizers. The dual-fluid units were effective at flows **as** low as 0.3 gpm, while the lowest consistently effective single-fluid nozzle needed 0.75 gpm to extinguish fires. These values are considerably below typical standard sprinkler system flow rates for a similar volume; the literature indicates that there is a minimum critical flow rate of about **4** gpm per 100 ft^3 of protected space for standard sprinkler systems [Cotes, 19921. This critical flow would equal over 8 gpm for the volume of the fuel fire test chamber.

Successful development **of** fine mist fire suppression systems hinges on the identification of atomizers/nozzles and a layout geometry to efficiently and effectively distribute a uniform concentration **of** fine mist droplets throughout the protected space. From our perspective, this means that fine mist systems will be particularly effective where they can be configured to "flood" the protected space, either by using larger droplet sizes (100 to 150 pm) and slightly higher water flow rates, or by installing dual-fluid systems that are designed for wide dispersion and high gas discharge velocities in order to push the finer droplets (below ***60*** pm) to the combustion zone in the fire.

The ability of fine mists to penetrate fire plumes with proper nozzle/atomizer design makes these systems priority candidates for replacement of halons in a wide range of applications. These include use in records rooms and computer facilities, and for fire and explosion suppression in areas exposed to fuels and combustible gases. In other research, ADA has demonstrated the ability of fine mists to quench the propagation of hydrogen/air explosions at concentrations near the lower explosive limit **[Butz,** et. al., 19931. These applications merit further investigation.

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