

Application of Fine Water Mists to Hydrogen Deflagrations

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Background

Hydrogen is explosive when mixed with air over a wide range of concentrations. The lower limit of flammability is 4% (H_2 by volume), and a mixture of hydrogen and air will burn at H_2 concentrations as high as 75% [1]. A situation was identified where hydrogen could be generated in a closed space, to a level where the lower explosive limit was reached and exceeded. In fact, concentrations as high as 15% could possibly occur, in the presence of ignition sources. A method was sought to attenuate or quench combustion of the mixture.

The mechanism for the explosion of a hydrogen/air mixture at low concentrations is a deflagration rather than a detonation. The critical difference between a deflagration and a detonation is the speed at which the combustion reaction propagates. In a deflagration, a fraction of the heat released upon combustion is conducted ahead of the flame front, and the adjacent gaseous mixture is heated to the point where combustion is initiated. The propagation of the flame front is thus controlled by the rate of heat transfer and the ignition temperature of the mixture. The velocity of the flame front is a function of the pressure and temperature of the mixture, but for hydrogen is in the range of a half meter to several meters per second. In a detonation, the pressure discontinuity at the shock front causes sufficient heating to produce ignition; thus the propagation travels at the speed of the shock.

Since heat transfer is critical to the deflagration mechanism, any process that reduces the rate of heat transfer has the potential to attenuate or quench the combustion reaction. A fine mist water spray dispersed in a space that holds a combustible hydrogen/air mixture should either reduce the flame propagation rate or possibly quench the combustion reaction. Recent modeling has indicated that there is the capacity in a spray of droplets below 100 microns diameter to transfer heat at a significant rate in the form of the heat of vaporization of the droplets [2]. The fine water mist could be injected into the space in addition to or as a replacement for the standard fire extinguisher sprinkler system.

The purpose of the research effort reported here was to investigate the effect of a fine water mist on the propagation of a deflagration in a hydrogen-air mixture. The impact of the fine water mist was studied with two different spray droplet size distributions. Tests were

conducted in a chamber about two meters in diameter and two meters in length. The chamber was a pressure vessel capable of accommodating transient overpressures of 100 psig.

Modeling of Fine Water Mist Heat Transfer

One important aspect of the design of the fine water mist experiments is the determination of the concentration of small droplets in the protected space. This is significant because the rate at which the droplets absorb heat from the hydrogen-air reaction is directly proportional to their size and concentration in the mixture. One approach to the definition of the required mist concentration is to calculate the heat liberated in the hydrogen combustion process, and then match the absorption capacity of the fine water mist to this value. The biggest unknown in this process is the prediction of the rate at which the hydrogen combustion will take place.

A spreadsheet was prepared to calculate the hydrogen heat of combustion as a function of hydrogen concentration. The results are presented in Figure 1, where the heat of combustion in Btu/ft^3 is indicated on the ordinate. Note that the plotted line reflects the lower limit of combustion of 4% hydrogen in air, and increases to 29.5%, where the stoichiometric ratio is one. At concentrations greater than 29.5%, there is insufficient oxygen to burn all the hydrogen present in the mixture, so that the process is oxygen-limited, and the combustion product gas mixture will contain unburned hydrogen.

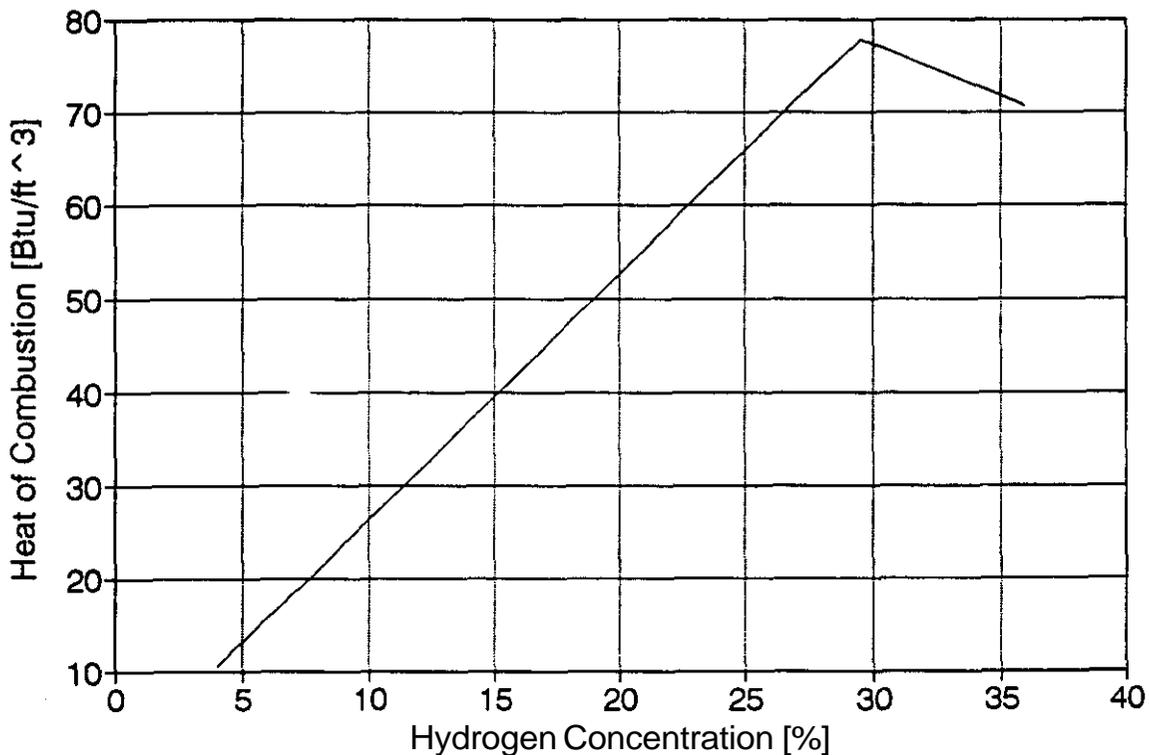


Figure 1. Hydrogen Heat of Combustion as a Function of Concentration in Air

The significant result here is that near the lower limit of combustion, there will be 10 to 30 Btu/ft³ of heat generated in the combustion process. Because of the **low** concentrations present, it is expected that the deflagration event will take between one and three seconds to propagate through the hydrogedair mixture in the test chamber.

The next step in the design process was to formulate a calculation of the heat transfer rate in the fine water mist in the chamber. The equation that was employed assumed that the water droplet was stationary with respect to the surrounding air, with a fixed Nusselt number of 2 (Nusselt number is a dimensionless ratio of characteristic length to boundary layer thickness used in heat transfer). This is a reasonable assumption because at diameters less than 100 microns, the small mass of each water droplet results in very little momentum [3]; the droplet very quickly comes to rest relative to the surrounding flow upon injection into the test chamber. The calculation used a fixed mass of water in a unit volume, distributed as droplets of diameter d . The rate at which heat is transferred to the droplets is a function of the temperature difference between the droplet surface and the bulk gas surrounding the droplets.

Results of the calculation are presented in Figure 2, as a function of droplet diameter. Separate curves are presented for three bulk gas temperatures. For reference, the minimum combustion temperature for hydrogen is about 1000°F. The impact of the expanded surface area of the smaller droplets is obvious: there is a significant increase in heat transfer rate for droplets below 100 microns in diameter. The graph shows that for 50 micron droplets, the heat of combustion for a hydrogen concentration near the lower explosive limit (LEL) could be absorbed in about one second at the water content level of 5 gallons per 1000 ft³. The propagation velocity of a hydrogen deflagration is a function of the temperature, pressure, and concentration of the mixture, but for concentrations near the LEL and conditions near ambient, the rate is on the order of a fraction of a meter to a few meters per second. **Thus** the water content used in the heat transfer rate calculation presented here is probably sufficient to affect the propagation of the deflagration event.

The water injection rate design requirement then is translated into the time needed to accumulate 5 gallons of fine mist droplets per 1000 ft³ of chamber volume, to provide the level of heat capacity indicated in the graph. For the test chamber used in the experimental work, a water injection rate of 1 gpm will reach this level in about one minute. The scaled injection rate for a standard fire sprinkler system is about 18 gpm, so that the fine water mist rate would be considerably reduced from the baseline sprinkler case.

The experimental approach was thus to perform a series of tests in which a fine water mist was injected into a mixture of hydrogen and air, which was then ignited. Several tests were conducted with only the gas mixture in the chamber in order to establish a baseline; in the others, the length of time during which mist was injected was varied to control the concentration of water droplets at ignition.

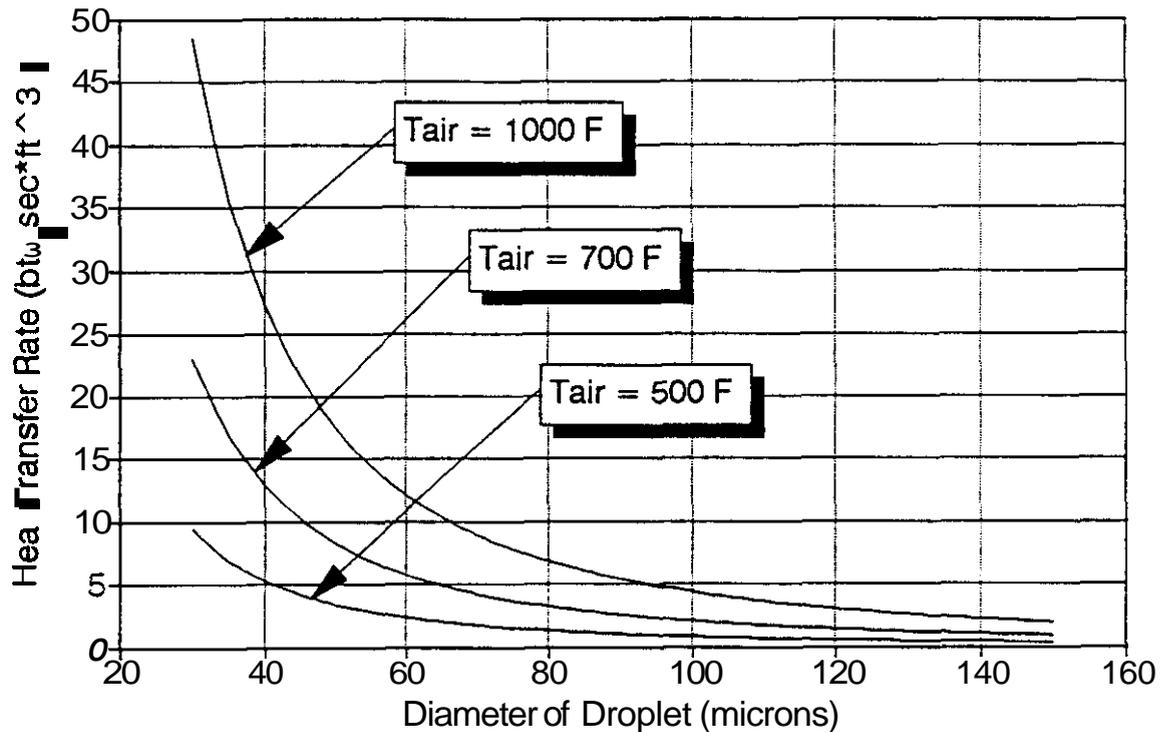


Figure 2. Heat Transfer Rates for Fine Water Mist Droplets

Test Facility

A chamber well-suited for performance of the deflagration tests was found at the Denver Research Institute, University of Denver. The chamber is a cylinder approximately 2 meters in diameter and 2 meters in length, oriented with a horizontal axis. The chamber is made from one inch thick steel, and is designed to contain transient overpressures up to 100 psig. It is equipped with a hinged cap at one end to allow full-diameter access the interior, and has numerous flanged penetrations for visual, electrical and fluid-flow access. The chamber presents an ideal environment for the hydrogen deflagration tests.

The chamber was equipped with pumps to permit a vacuum to be drawn within, so that the injected gas mixture could be customized to match test conditions over a wide range of interest. A known concentration of hydrogen would be introduced into its sealed volume, mixed with air and then ignited. A hood was installed above the hinged cap, and was ducted to a large capacity fan, so that upon opening the cap at completion of a test, the combustion product gases were immediately diluted with room air and vented up a chimney external to the facility.

A water spray header was installed to which the standard sprinkler heads or fine water mist nozzles were attached. A second header was added to supply air to the two-fluid nozzles used for generation of the fine water mist. Other modifications were made to equip the

chamber with a water drain system by which water sprayed during a test could be removed. The lines which supply air and water to the test chamber were instrumented to allow measurement of flows during operation of the sprinkler heads or water mist nozzles; solenoid control valves for air and water were also installed.

Redundant electrical ignition systems were placed in the chamber to initiate the deflagration. The igniters were powered by a capacitive discharge system, operated at 3.5 KV; approximately 10 joules of energy was discharged across each igniter during the event. The electrodes were spaced about 19 mm (3/4 in.) apart, with a fine copper wire (0.05 mm, or 0.002 inch diameter) attached to span the gap. At discharge, the copper wire is vaporized, and the successive arc follows the ion path of the wire vapor between the electrodes. Timing of the ignition is controlled by a programmable logic controller that was used to sequence the test events.

The chamber was instrumented with pressure transducers and fine-wire thermocouples to monitor the tests. The pressure transducers were piezoresistive units with an absolute calibration. The thermocouples were 0.25 mm (.010 in) diameter with a time response of about 30 milliseconds. Each thermocouple was connected to a module that provided an ice point reference and amplified the signal before it was fed to the data acquisition system.

All 6 instrumentation channels were input to a high speed, 12-bit digitizer that was ~~turn~~ connected to a personal computer system. Data were scaled with appropriate calibration coefficients and stored in files on the personal computer, where they were available for further analysis and graphic display.

The experiments were completed in an automated sequence that was controlled by a programmable logic controller (PLC). The controller was programmed to initiate the digital data acquisition system, actuate the solenoid valves that controlled the flow of air and water to the fine mist atomizers, charge the ignition power supplies, and to finally fire the igniters. Five seconds after ignition the mist atomizers were shut off. The use of the PLC allowed the time of discharge and corresponding concentration of mist in the test chamber to be easily changed during the test series.

A transparent polycarbonate window was installed in one of the chamber access ports to allow a video camera to document test events. A schematic of the test chamber outfitted with instrumentation and controls is shown in Figure 3.

Hydrogen concentration in the test chamber was controlled by measuring the pressure of hydrogen as it was flowed into the chamber after evacuation to a vacuum of less than one mm of mercury. The atomizer nozzle air flow was used to assist in the mixing of hydrogen and air in the test chamber, so that a uniform mixture was present at ignition. This was done by backfilling the chamber with air after injection of the hydrogen to a pressure that was below the desired gas pressure at ignition. The additional air needed to bring the pressure of the mixture to one atmosphere was then provided by the atomization air during injection of the fine water mist by the atomizing nozzles. The backfill pressure that was needed was therefore a function of the prescribed operating time for the atomizers. The atomizer operating time was varied over a range of 5 to 90 seconds during the testing; the air backfill pressure was also varied in order to provide a consistent pressure at ignition of one atmosphere in the chamber.

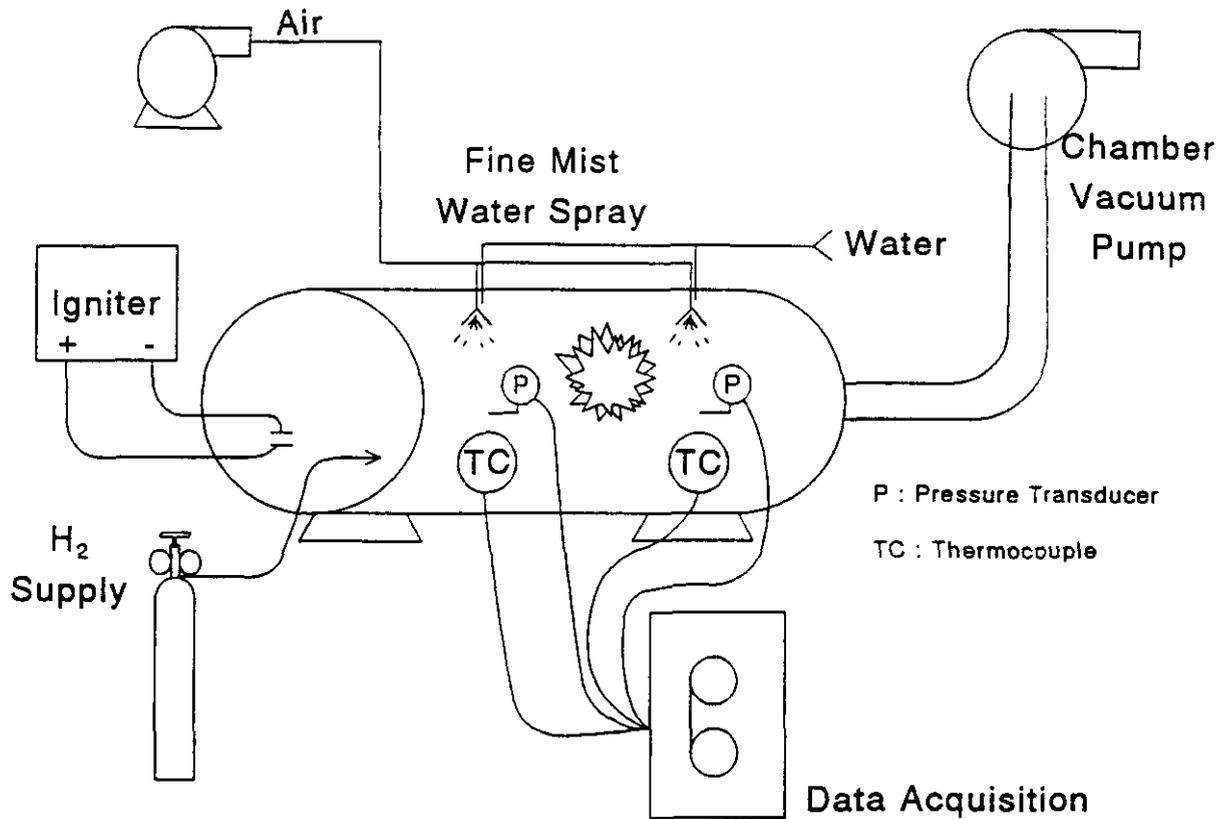


Figure 3. Schematic of ~~Deflagration Test~~ Chamber

Test Procedure

To facilitate comparison of the data obtained from the several tests to be performed in the chamber, a standard test procedure was established and followed for all tests. The procedure included activities in nine categories, and is summarized as follows:

- o Set test operating conditions: All test parameters are confirmed in this activity, including the pressure of hydrogen to be injected into the chamber (which sets the hydrogen concentration for the test), the sequence timer intervals, flowrates for air and water to the atomizers, and the target air pressure at backfill in the chamber.
- o Confirm chamber internal configuration: The atomizers were checked, all instrumentation was confirmed as operational, the ignition wires were installed and the chamber interior was inspected to assure that all test preparations were complete.
- o Evacuate chamber: The chamber door was closed, the vacuum pumps were started and the valves that isolate the chamber were opened to begin pumping the air from the chamber. As the vacuum pump drew air from the chamber, the bolts on the door seal were tightened, and the progress of the evacuation was monitored. At maximum vacuum, the chamber was isolated by closing

the valves and vacuum gauges were monitored to assure that the chamber was sealed and holding the vacuum.

- o Hydrogen fill: Hydrogen was added to the chamber via an injection line and control valve. The quantity of hydrogen in the chamber was monitored via a large diameter absolute pressure gauge that was attached to the chamber. Hydrogen was added until a previously defined pressure was achieved. The hydrogen source was then isolated from the chamber by two hand valves, a check valve and a flame arrestor.
- o Air fill: The test chamber was backfilled with air to a predetermined pressure, calculated to produce a total of one atmosphere at the time when the igniters were fired. Chamber pressure was monitored on the large diameter pressure gauge during the backfill.
- o Test performance: After a final check of all systems, the PLC was started to actuate the air and water valves, charge the firing power supplies, initiate the data acquisition system, and fire the igniters. The only activities performed by test personnel were to put the video camera into "record" mode and to start the logging of flow data on another data collection system.
- o Test completion: Upon discharge of the igniters in the chamber, a series of items were completed, including confirmation of power supply discharge, verification of data acquisition trigger, storage to disk of digital data records, and stopping of the video camera. If there was a successful deflagration, a procedure was followed to vent the chamber contents to the atmosphere; if the fine water mist had quenched the deflagration, an alternate procedure was followed to dilute the explosive mixture in the chamber and vent the gases (now diluted below the explosive limits) to atmosphere.
- o Quench dilution procedure: The first step in this procedure was to vent pressure in excess of Denver ambient pressure (about 12 psia) to atmosphere, where the vent pipe mixed with ambient air above the roof of the building in which the chamber was housed. A cylinder of nitrogen gas was then added to the mixture in the chamber while the vent valve remained open. The nitrogen gas served to dilute the explosive mixture as the tank was venting. This process required about 45 minutes to dilute the explosive mixture to a level well below the lower explosive limit of hydrogen in air.
- o Successful deflagration procedure: If the mixture was successfully ignited, the combustion products were immediately vented to atmosphere via the vent valve, and the chamber was opened. The facility vent fan was started, and the chamber door opened so that the combustion products could be diluted and drawn from the chamber. Water sprayed into the chamber was drained to an external holding tank, then pumped into the building drain system. The open chamber was purged for 15 minutes with room air to completely remove combustion products from the chamber interior.

Test Results

A total of 20 tests were performed in this initial series at a nominal hydrogen concentration of 6% in air; actual concentrations ranged from about 6.1% to 6.8%. Five of the tests were **run** with no spray in the chamber, in order to document the performance of the facility, to provide a baseline for expected pressure profile in a hydrogen deflagration, and to evaluate the consistency of tests that were **run** in the chamber. Three tests were **run** with the standard fire protection sprinklers that normally are used in the space that was modeled in the chamber. Twelve tests were **run** with the fine water mist atomizers operated prior to ignition.

The no-spray tests demonstrated very consistent ignition and **peak** pressures among the events. Peak pressures were about 2.2 bar, ± 0.2 bar (33 psia, ± 3 psi). Measured rise time to the peak pressure was about one second.

Water mist was then added to the mixture before ignition. The water flowrate for all mist tests was 3.8 liters per minute (1 gpm) total to the two atomizers installed in the chamber. Spray time for the first water mist test was about 45 seconds; there was no quench of the deflagration observed. The spray time was increased to 90 seconds for the second mist test, where the deflagration was successfully quenched, and did not propagate through the mixture. Additional tests were performed to define the threshold at which the deflagration could be consistently quenched.

Finally, a series of ~~three~~ tests were conducted to determine if there was any effect of the **standard** fire protection sprinklers on the deflagration event. There was no discernible impact from the **standard** sprinklers, operated at flowrate of 68 liters per minute (18 gpm).

When the fine water mist quenched the deflagration, there was no evidence of pressure rise on the records. The thermocouple records also did not show any indication of the propagation of combustion beyond the immediate vicinity of the igniters.

In fine water mist events that did deflagrate, there was pronounced evidence of the cooling provided by the mist droplets. Figure 4 presents thermocouple histories for two tests, one without mist and one with mist injection where the deflagration did occur. The cooling provided by the mist is obvious in the temperature traces, where the measured values for the mist test **are** seen to be about 200°F cooler than temperatures for the dry test.

A corresponding effect is seen in the pressure profiles, shown in Figure 5. Here the peak pressure for the mist test is about 0.3 bar below the peak for the dry test; typically, the pressure attenuation **seen** for these events is about 10%. There is a definite reduction in **peak** pressure and temperature due to cooling by the fine water mist in events where the deflagration is successfully propagated.

Overall results from the fine water mist tests are **summarized** in Figure 6. Here the length of time for which fine mist was injected is plotted against the success of the deflagration quench. The threshold is found at about 60 seconds of injection time; all events with greater than 60 seconds of mist successfully quenched the deflagration. Sixty **seconds** is the time required to inject about 0.7 liters of water per m³ (5 gal per 1000 ft³) of hydrogen/air **mixture**.

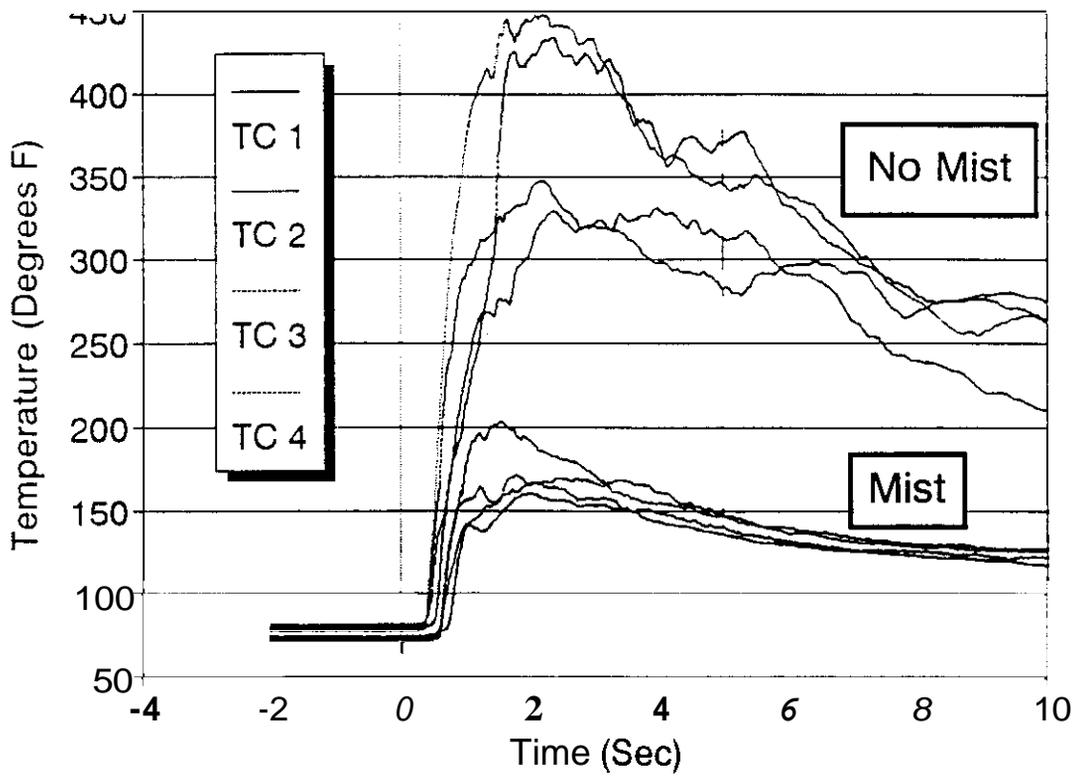


Figure 4. Temperature Histories for Deflagration Events with and without Fine Water Mist

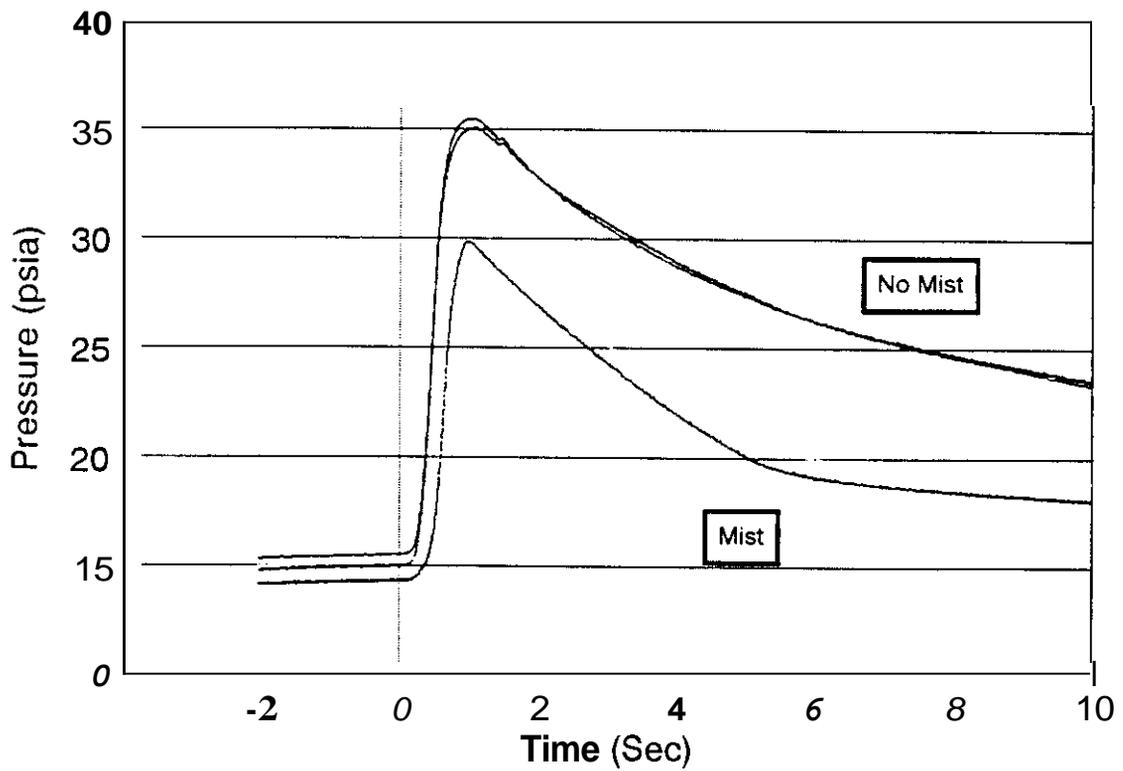


Figure 5. Pressure Histories for Deflagration Events with and without Fine Water Mist

Tests conducted with two standard fire sprinkler nozzles operating in the chamber at a total flow rate of 68 liters per minute (18 gpm) showed no ability to-quench the deflagration events. The hydrogen mixture was easily ignited, and the measured pressure profiles were very similar to those from dry tests at the same hydrogen concentration. There was a measurable reduction in temperatures measured during the standard sprinkler events.

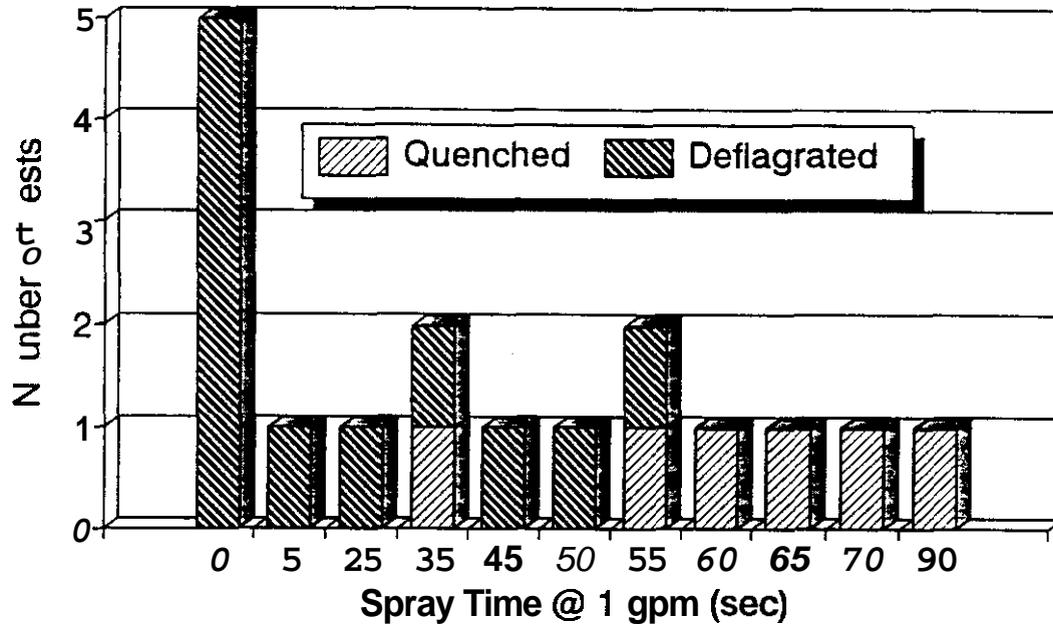


Figure 6. Summary for Tests Performed with a 6%Hydrogen Mixture Ignited in the Presence of Water Mist.

Conclusions and Recommendations

A test fixture for the investigation of the effect of fine water mists on hydrogen deflagrations has been assembled and successfully operated. Consistent deflagration events have been conducted in the chamber. The facility was then used to characterize the impact of mists on deflagration events.

The quenching of a hydrogen deflagration at a concentration of 6% in air was demonstrated with a fine water mist. The mist concentration required for successful quench was found to be 0.7 liters per m³ of protected space. This threshold is believed to be a function of the hydrogen concentration in the chamber at the time of ignition. At mist concentrations below the threshold there was pronounced evidence of the evaporation of water droplets during the deflagration event. The cooling effect was seen in reduced temperatures as measured by the thermocouples in the test chamber and by a reduction in the measured peak pressure during the deflagration event.

It appears that a viable explosion suppression system could be based on the injection of fine water mists into the protected space, if there is time available for the mist concentration to

reach the level required to assure the quenching of an ignited mixture. Tests at higher hydrogen concentrations would be useful in further delineating the threshold as a function of hydrogen fraction in the protected space. Another parameter of interest in additional tests would be the *size* of droplets produced in the atomizers that provide the mist. Since the process is postulated to be one of heat transfer, smaller droplets would result in additional surface area and potential ability to quench the deflagration event at lower water mist concentrations.

References

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Acknowledgments

This work was performed under funding from the US Navy. Tests were conducted in part by Patrick French of **ADA**, and were supported by Tim Samaras and Bob Lynch of **DRJ**. The test chamber was outfitted for these tests by George Crater of **ADA**.

