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Benchmark Enclosure Fire Suppression Experiments – Phase 1 Test Report

Thomas K. Blanchat, Robert T. Nichols, Victor G. Figueroa

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Thomas K. Blanchat, Robert T. Nichols, and Victor G. Figueroa
Fire Science and Technology Department
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1914

Abstract

A series of fire benchmark water suppression tests were performed that may provide guidance for dispersal systems for the protection of high value assets. The test results provide boundary and temporal data necessary for water spray suppression model development and validation. A review of fire suppression in presented for both gaseous suppression and water mist fire suppression. The experimental setup and procedure for gathering water suppression performance data are shown. Characteristics of the nozzles used in the testing are presented. Results of the experiments are discussed.

ACKNOWLEDGEMENTS

This report concludes a multi-year study of phenomena and data from a suite of unique fire experiments. The authors would like to thank the following individuals for their participation in this effort.

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1. Introduction

This report documents the Phase 1 suppression experiments performed for the Defense Threat Reduction Agency (DTRA) funded under the Sandia National Laboratories WFO Proposal 03920715-22 and IACRO 0541211 "FUEL FIRE TEST AND MODELING DEVELOPMENT PROGRAM". The Phase 1 task is described below.

Perform Benchmark Experiments - Sandia shall perform up to eight benchmark experiments comparing water spray, water mist, water fog and high-pressure foam suppression systems against fires with simulated high value assets. The effort would be to apply existing commercial off the shelf (COTS) agents and delivery systems in large-scale extinguishment experiments in the SNL Fire Laboratory for Accreditation of Models and experiments (FLAME) Facility and/or the Sandia Enclosed Fire Test Facility. The goal is to obtain data characterizing simulated weapon thermal response (represented by a calorimeter) to a fully involved jet fuel fire and subsequent suppression of that fire. Data to support other system measures of merit will be acquired, as possible.

This work consisted of several tests conducted to characterize current fire suppression technology. Data from these tests can be used to validate SNL fire physics codes (VULCAN, FUEGO) that include fire suppression models.

1.1. Purpose and Scope

The objective of this work was to perform a series of new fire benchmark tests which explore modern fire suppressant agent dispersal systems and new suppressants that may be used for the protection of high value assets. The results of the testing (divided into three phases) were to provide required boundary and temporal data necessary for model development and validation. The testing and future modeling efforts were to support the development of various fire suppression strategies, techniques and/or systems for use in new and retrofitted facilities and to provide design options for the building designer with regard to fire suppression, given the multitude of construction techniques.

The Phase 1 benchmark experiments were limited to one fuel (JP-8) and to only one type of suppressing agent that is commercially available, water mists. This suppressant was chosen because VULCAN currently has the capability to model only gaseous or liquid droplet suppression. Moreover, due to the restricted capacity of the suppression system test apparatus, benchmark experiments were conducted with a limited number of nozzle sizes and flow rates.

These tests were conducted in the new Fire Laboratory for Accreditation of Models and Experiments (FLAME) facility located at the Thermal Test Complex (TTC), which is located in Albuquerque, NM at Sandia National Laboratories. This work included minor facility modifications to allow installation of fire suppression equipment. Testing also included short "shakedown" suppression tests to characterize the performance of the newly configured facility for the test series.

The scope of this set of experiments included:

1. The design and fabrication of a test apparatus,
2. The performance of one or more baseline tests to corroborate the general behavior of the test facility fire environment and confirm the operation of all equipment,
3. The performance of several benchmark fire and subsequent suppression tests to include data on the necessary initial and boundary conditions for modeling purpose, as well as simulated asset response.

1.2. Deliverables

The deliverables consist of the presentation of a final report to the DTRA that describes in detail the following:

1. The authority by which this series of experiments was performed.
2. The objectives and scope of the experiment series.
3. The identification of the key parameters governing the design of the experimental matrix and the basis for their selection.
4. A complete description of the test apparatus, including detail drawings and photos. Video coverage of the experiments will be furnished with the report.
5. A detailed description of the procedure as to how each test was performed.
6. An analysis of the data to include the amount of suppressant and time required to suppress/extinguish the fire.
7. A presentation of the results that discusses fire suppression and simulated asset response.
8. A discussion of the results including areas of concern and uncertainties that may warrant further investigation.

1.3. Summary

This report has been prepared to meet the above deliverables. In what follows, a review of fire suppression in presented for both gaseous suppression (Appendix A) and water mist fire suppression (Chapter 2). The focus then shifts to water suppression where some recent modeling work with the SNL fire code VULCAN is described. The experimental setup and procedure for gathering water suppression performance data are shown. Characteristics of the nozzles used in the testing are presented. Results of the experiments are discussed.

2. Background

Current systems for suppressing fires are based on standard practices for slow growing fires in structures that contain low flammability contents similar to those found in common households. Under extreme fire conditions and large ventilated spaces in which fires spread rapidly, these approaches are impractical, largely ineffective at rapid extinguishment and can put responders in harm's way. Select military facilities and the high consequence assets therein may be subjected to these large, rapid spreading interior fires. The protection of these facilities therefore requires more effective fire suppression techniques and well defined strategies to limit the spread of fire and to achieve rapid extinguishment.

The Defense Threat Reduction Agency (DTRA) supports the military services in nuclear hardening and survivability issues, analysis technology, safety, and surety. As a result of this responsibility, action items were identified by recently completed Fire Hazard Analysis (FHA) performed by DTRA for two AFMC depot storage facilities. Some of these items are defined below:

1. Explore current and future fire suppression techniques that limit the volume of suppressant material required to quickly extinguish liquid fuel fires.
2. Explore personnel safety issues so that an on-site commander's decision to engage personnel is not in conflict with his mission to protect high consequence assets.
3. Provide modeling tools for the analysis of possible fuel fire threat environments. These tools are to be developed in order to assist the military services in the evaluation of high consequence asset response in an abnormal fuel fire environment. Scenarios include the modeling of fires that are started from spilled hydrocarbon fuel (e.g. JP-8). This effort includes the documentation of previous benchmark tests where a comparison of both test data and model simulations were performed.
4. Develop and execute additional benchmark testing to calibrate fire models that aid in the development of designs that protect high consequence assets in the event of an abnormal fuel fire environment. Testing is to include extinguishment under some of the newer fire suppression approaches other than standard overhead sprinklers.

To address these action items, a multi-year program was proposed that has two phases of benchmark experimentation. Under Phase I Sandia was to perform fire suppression experiments against fires with simulated high value assets. This effort was limited to existing COTS agents and delivery systems (water spray, mist, fog, gaseous suppressants, high-pressure foam, or aerosols) in large-scale extinguishment experiments.

Phase II testing would employ sophisticated instrumentation to measure droplet sizes and distributions (Phase Doppler Particle Anemometry, PDPA) and droplet penetration into the flame zone (Particle Image Velocimetry, PIV) to validate suppression models. The goal was to obtain model validation quality data to support anticipated future numerical predictions at prototypic (defined above) scenario scale that will characterize weapon thermal response to a fully involved jet fuel fire and subsequent suppression of that fire. Data to support other system measures of merit would be acquired, as possible.

Following Phase II testing SNL and DTRA would identify and perform a field scale experiment based on one of the identified Fire Hazard Analysis Fire Scenarios, using prototype systems suggested by the Air Force Research Laboratory (AFRL). A post-test numerical prediction of the field scale experiment would be performed to evaluate VULCAN performance. This report addresses Phase I of section 3.3.5 Perform Benchmark Experiments, from Annex A of the Statement of Work, Fire Suppression Development for Sandia National Laboratory, (FY 05-FY 09 Funding Years), March 2005.

Benchmark testing provides the necessary information for design options for fire suppression, containment, surety, and new techniques in fire fighting. New small sized, low volume fire suppression techniques are important in the safety of high consequence assets.

Model development efforts are being spent towards the inclusion of a fire suppression module into VULCAN. The model development work is being done in a parallel effort by Sandia National Laboratories under other agency funding. Results of these models may be compared against field test data to calibrate additions made to the code.

2.1. Factors that Affect Fire Suppression

There are a number of factors that influence how a fire reacts to the application of a suppressant. There is no one system or suppressant that may be applied to all possible environments or all types of fires. Some suppressants and application techniques will work well for some types of fires in some environments but not for others. Some of the key parameters that govern a fire’s response to the application of a suppressant are listed below:

1. Type of fuel (liquid, solid, gaseous),
2. Enclosure size (volume, height, etc.),
3. Clutter (volume ratio and size),
4. Ventilation,
5. Type of suppressant (water, solid, gaseous),
6. Morphology of suppressant and application technique,
7. The mechanism the suppressant uses to extinguish a fire.

Most suppressants work on three basic principles. They either inert the atmosphere so that combustion is not supported (dilution), react with the radicals in the fuel so that combustion cannot be supported (chemical), or take away the heat energy, i.e., the ignition source and stop the chain reaction (thermal). Some suppressants may possess more than one of these mechanisms. In fact, most scenarios require a suppressant to have more than one mechanism for extinguishing a fire. Not only must the fire be extinguished, but the suppressant must also ensure the fire does not re-ignite.
Other properties of a suppressant that are desirable are:

1. The suppressant must be nontoxic, i.e. increase the surety of survival of personnel in the area and first responders,
2. The suppressant must not be harmful to the environment, i.e. it has a short life in the atmosphere, low or zero ozone depletion potential, low global warming potential.
3. It must be commercially available,
4. It is effective for the type of fire that is expected or may occur at the facility, and
5. It does not harm or compromise the performance of the high consequence assets that it is installed to protect.

In order for designers to specify an effective fire suppressant system for any given facility an understanding of how the suppressant interacts with each of the variables listed above and how they affect its performance must be obtained.

The following section is reproduced from the appropriate section of Reference [5]. "Water misting systems allow the use of fine water sprays to provide fire protection with reduced water requirements and reduced secondary damage." Calculations indicate that on a weight basis, water could provide fire extinguishment capabilities better than those of halons provided that complete or near-complete evaporation of water is achieved. Since small droplets evaporate significantly faster than large droplets, the small droplets achievable through misting systems could approach this capability. Reference [6] establishes 1000 microns (micrometers, μm) or less as being the water droplet size for a system to be designated as a water misting system; however, many misting systems have droplet sizes well below this value. Water misting systems extinguish fires by three mechanisms:

1. heat absorption through evaporation and, to a lesser extent, vapor-phase heat capacity,
2. oxygen dilution by the water vapor formed on evaporation, and
3. radiative heat obstruction by the mist.

A detailed review of water misting has been written by the Navy Technology Center for Safety and Survivability and Hughes Associates [7]. More recent reviews are presented in [8, 9]. Water mist is being evaluated both as a possible replacement for total-flooding Halon 1301 [10] systems and for use in hand-held extinguishers [11].

At the request of the EPA, manufacturers of water misting systems and other industry partners convened a medical panel to address questions concerning the potential physiological effects of inhaling very small water droplets in fire and non-fire scenarios. Disciplines represented on the medical panel included inhalation toxicology, pulmonary medicine, physiology, aerosol physics, fire toxicity, smoke dynamics, and chemistry, with members coming from the commercial, university, and military sectors. The executive summary of the final report states the following:

> "The overall conclusion of the Health Panel's review is that water mist systems using pure water do not present a toxicological or physiological hazard and are safe for use in occupied areas. The Panel does not believe that additional studies are necessary to reach this conclusion. The Health Panel recommends that additives be evaluated on a case-by-case basis depending on the toxic properties of the additive and the concentration at which it is used."

As a result of this study, the EPA is listing waster mist systems composed of potable water and natural sea water as acceptable without restriction under SNAP. Water mist systems comprised of mixtures in solution must, however, be submitted to EPA for review on a case-by-case basis.

There are two basic types of water mist suppression systems – single fluid and twin fluid. Single-fluid systems utilize water stored or pumped under pressure; twin fluid systems use air, nitrogen or another gas to atomize water at a nozzle. The systems can also be classified according to the pressure in the distribution system piping as high pressure (above 500 psia, 34.5 bar), intermediate pressure (175 to 500 psia, 12.1 to 34.5 bar), and low pressure (175 psia, 12.1 bar or less). Both single- and twin-fluid systems have been shown to be promising for fire suppression. Single-fluid systems have lower space and weight requirement, reduced piping requirements and easier system design and installation; twin-fluid systems require lower water supply pressure, larger nozzle orifices (greater tolerance to dirt and contaminants and may allow the use of higher viscosity antifreeze mixtures), and increased control of drop size.

The performance of a water mist system depends on the ability to generate small droplet sizes and the ability to distribute mist throughout a compartment in concentrations that are effective. Suppression effectiveness depends on five factors:

1. droplet size,
2. droplet velocity
3. spray pattern,
4. momentum and mixing characteristics of the spray, and
5. geometry and other characteristics of the protected area.

Water mist systems are reasonably weight efficient. The use of small-diameter distribution tubing and the possible use of composite, lightweight, high-pressure storage cylinders would increase this efficiency. It may also be possible to integrate a central storage of water for use in several potential fire locations.

The major difficulties with water mist systems are those associated with design and engineering. These problems arise from the need to generate, distribute and maintain an adequate concentration of the proper sized drops throughout a compartment while gravity and agent deposition loss on surfaces deplete concentration. Water mist systems have problems extinguishing fires located high in a space away from discharge nozzles. Other concerns that need to be addressed are:

1. collateral damage due to water deposition,
2. electrical conductivity of the mist,
3. inhalation of products of combustion due to lowering and cooling of the smoke layer and adhesion of the smoke particles to the water drops,
4. egress concerns due to loss of visibility during system activation,
5. lack of third-party approvals for most or all applications,
6. lack of design standards [12]. Concern has also been expressed about the possibility of clogging of small nozzle orifices used in some systems,

7. low temperatures that may hinder the storage, discharge and evaporation,
8. systems which are likely to be bulky, and
9. systems which are not expected to be distributed as uniformly as halocarbon and other gaseous agents.

2.2. Water Mist Literature Review

The literature study conducted by Yoon et al [13] provides some generalizations about the important parameters that govern fire suppression of liquid fuel fires when water mist is used as a suppressant. The most relevant studies are those in which liquid fuels were used in pool fires that were conducted either in the open or in compartments. Conclusions drawn by the respective investigators for their specific experiments are presented here in a summary format.

The primary cooling mechanisms observed in the aforementioned studies is the abstraction of heat from the fuel by water droplets within the fuel i.e. thermal cooling by means of droplet evaporation and subsequent oxygen displacement. The modeling studies have also shown that the radiant energy emitted by the flame was attenuated by water droplets.

These investigations indicate that the rate of water droplet evaporation was directly proportional to the fire heat release rate and the water mass flow rate. Thus, the spray mass flow rate, droplet size of the spray and the heat release rate of the fire were found to be the controlling parameters in the cooling of a compartment fire. The ability of the water spray to remove heat in general is increased as the mass flow rate of the water spray increased. However, the variation of water droplet evaporation rate (size dependent) is an important parameter in order to achieve an efficient fire suppression condition. These studies indicate that fire suppression is very sensitive to the spray droplet size and velocity initial conditions. Therefore, it may be stated that effective water spray flux becomes more useful than injection pressure in fire extinguishment.

It is indicated that direct cooling of the fuel surface was found to be the driving mechanism for suppression when the spray momentum was large enough to overcome the buoyancy force of the plume. Oxygen displacement due to water vapor formation becomes the driving mechanism for the case where the spray momentum is not large enough to push the stagnation region to near the fuel surface.

It has been noted that the fire intensified in some cases due to enhanced mixing of the fuel and air if the water mass flow rate is not above some critical level. Modeling efforts indicate that turbulent mixing of the flame is enhanced and thus the local temperature increases temporarily upon spray injection. Therefore a larger water spray thrust may induce a faster burning rate due to a sufficient supply of air through entrainment.

In one study, the shape/geometry of the fire controlled the heat flux radiated to the pool surface and thus the amount of vapor formation was also affected by the fire shape. For this reason, the distortion in the fire shape due to water spray can contribute to the rapid extinguishment process.

A spray system which produces a smaller droplet size was more efficient at extinguishing the fire when injected at a 60° angle from the base for small laminar fires (30 cm diameter). Numerical studies show that an overhead (90°) injection configuration was more efficient at putting out fires for a larger scale (0.61 m x 1.22 m square burner) turbulent propane pool fire. It can be concluded that some transitional behavior from laminar flow to turbulence occurs around 0.5 m to 1.0 m assuming that the fuel type does not significantly affect the transitional behavior.

One study found that a water spray with a solid cone pattern and finer water droplet size was more efficient in extinguishing fires than one with a hollow cone pattern and generating a coarse droplet size. One study also indicated that the elevated temperature of upper smoke layers could have a major impact on the thermal response of sprinkler links.

2.3. VULCAN Water Spray Model Assessment

The effect of initial water spray characteristics on the suppression of a large-scale JP8 compartment pool fire was studied using the VULCAN suppression model [13, 18]. The fire scenario of Chow et al [14] was chosen for the evaluation study, in which the performance level of the current suppression model was assessed by comparing the numerical prediction of the model against experimental data.

The validation study [13] indicated that VULCAN produced results consistent with the existing experimental data. A parametric study on a large scale enclosure pool fire (2 m x 2 m burner centered on the floor in a 10 m x 10 m x 10 m compartment with an open ceiling) indicated that a water spray system which can produce small droplets with high injection speeds yielded the optimum suppression condition. However, a system that produces too small a droplet (below some critical diameter) will not produce suppression since it cannot overcome the buoyant force of the fire. A four-nozzle configuration seemed to be less efficient than the one-nozzle configuration when comparing spray penetration. The location of the stagnation zone between the downwardly injecting spray and the upwardly lifting fire plume was found to be an important parameter for the consideration of the preferred suppression condition. Also, the spray system with four nozzles induces a greater turbulent mixing between the fire and the air, resulting in a temporary increase in the local gas temperature. Results of this study showed that the current suppression model is capable of providing not only qualitatively useful insight, but also reasonably acceptable quantitative information.

3. Experiment Setup and Procedure

A series of fire suppression benchmark experiments were conducted in the new FLAME facility. For practical reasons, this series of benchmark experiments were limited to one fuel (JP-8) and to only one type of suppressing agent that is commercially available, water mists. This section describes the benchmark experiment setup.

3.1. Flame Facility

Liquid or gaseous hydrocarbon fires of meter scale can be performed in a controlled environment in the FLAME facility in the Thermal Test Complex at Sandia National Laboratories (Figure 1). The main test chamber of the FLAME cell is cylindrical in shape, 60 ft. (18 m) inner diameter with a height around the perimeter of 40 ft. (12 m). The ceiling slopes upwards (~18º) from the perimeter walls to a height of 48 ft. (15 m) over the center of the facility. A round hole at the top of the facility 16 ft. (4.9 m) diameter transitions to a 10 ft. by 12 ft. (3.0 m by 3.7 m) chimney duct. The outer walls are made of steel channel sections and are filled with water for cooling during tests.

The ground level of FLAME can be divided into three concentric sections. At the inner section of the facility is a fuel pan or gas burner. The facility can operate a gas burner (He, H_2, CH_4, etc.) or a liquid fuel pool (JP-8, methanol, etc.) from 1 m to 3 m in diameter. The middle section is a steel spill plate, which extends to a diameter of 6 m. The floor of the outer section is made of a steel grating, through which air is supplied to the FLAME chamber during fire experiments. FLAME is designed for flexibility in fuel types to evaluate radiation and combustion characteristics of light to heavy sooting fuels.

The combustion air flow is provided by a forced-draft fan that feeds supply air to the basement. A separate fan, the induced-draft fan, pulls on the exhaust duct, and is synchronized with the forced-draft fan to maintain zero differential pressure across the FLAME cell wall. The air flow in the absence of a fire has been characterized experimentally at the air ring in the basement and at the ground level. The air ring flow field was found to exhibit a pattern attributable to the 18 supply pipes carrying the air from the diffuser in the center of the facility to the air ring along the outer edges of the facility (Figure 2). The air flow at the ground level was found to be highest in the outer portion of the cell, and exhibited a large recirculation zone in the inner portion of the facility, where mean velocities were in the negative (downward) direction (Figure 2). The presence of a fire at the center of the facility is likely to reduce the recirculation because the air flow will be drawn inwards and entrained into the buoyant fire plume.

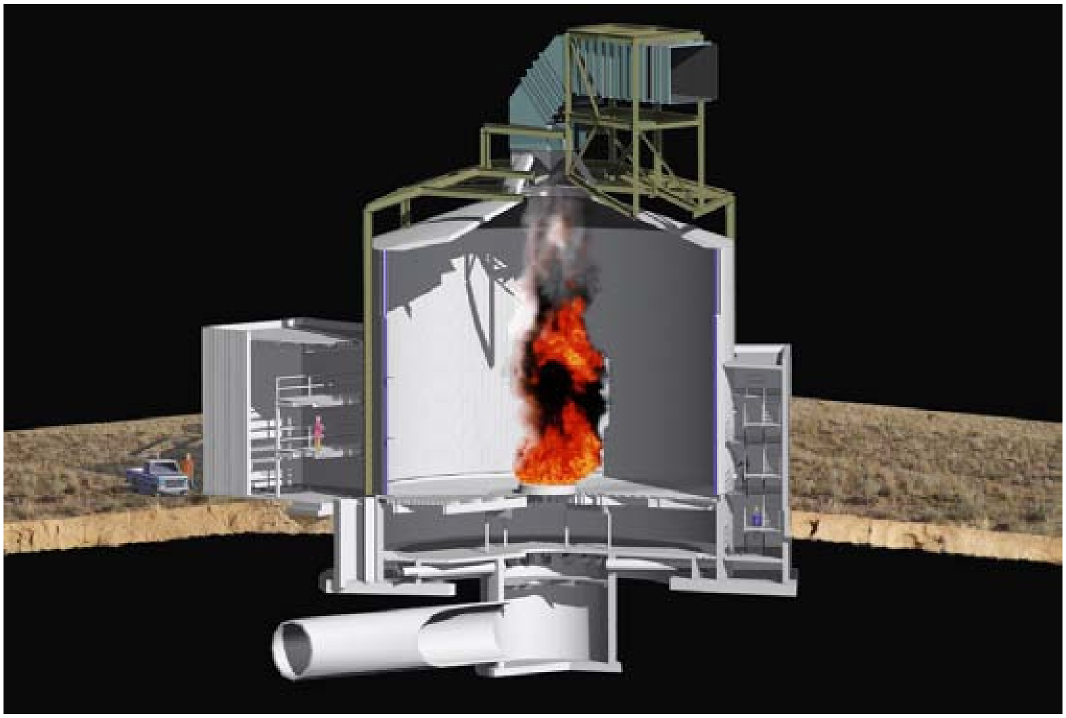
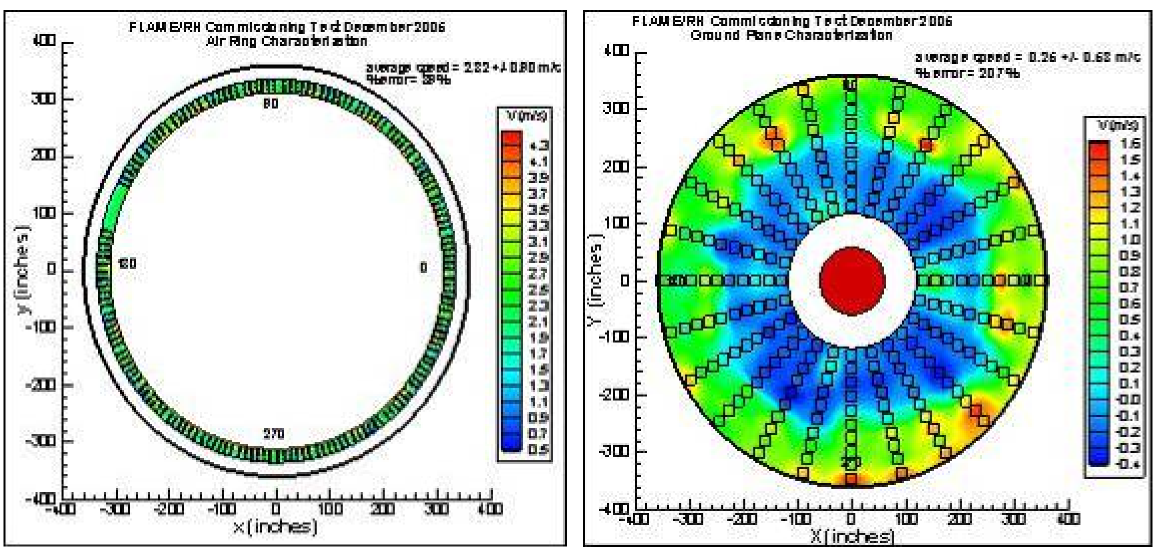


Figure 1. Fire Laboratory for Accreditation of Models and Experiments (FLAME).



Basement air ring

Ground level

Figure 2. Velocities at the Air Ring in the Basement and at the Ground Level.

Figure 3. 2-m Diameter Liquid Fuel Pan.

The FLAME cell was designed to withstand a 20 MW fire (nominally provided by a 3-m diameter JP8 liquid pool fire). Two fuel pans have been tested to date, a 2-m diameter and a 3-m diameter pan. Figure 3 shows a 2-m liquid pan (nominally a 4 MW heat release rate) set within the 6-m diameter splash plate.

3.2. Suppression System Apparatus

A test apparatus simulating a single-nozzle, water suppression system was assembled inside FLAME (see Figure 4). The apparatus consisted of: (1) a nominal 1-1/2" diameter, inverted L-shaped, steel pipe frame, (2) a nominal 1-1/2" high-pressure rubber hose, (3) a positive displacement pump, (4) a water reservoir, and (4) various nozzles. The diesel-powered high pressure/high volume spray pump was loaned to SNL by the Air Force Research Laboratory (AFRL, Tyndall AFB).

The location of the pipe frame was adjusted by moving the base of the frame along the diameter of the FLAME Facility. Four bolts on the base of the frame and four cables were used to secure the steel pipe frame once the desired location of the nozzle with respect to the pan was achieved. The 1-1/2" rubber hose connected the pipe frame to the pump and water reservoir (see Figure 5).

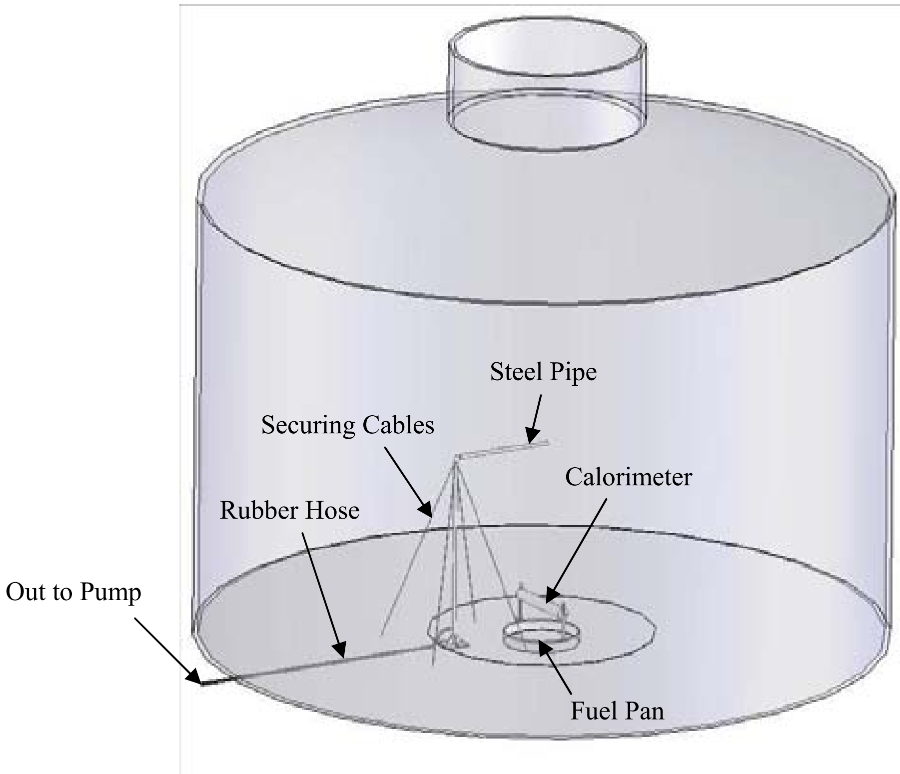


Figure 4. Experiment Layout.

Figure 5. High Pressure Pump and Water Reservoir.

Two alternative pipe configurations were used to increase the range of pressures delivered to the nozzle; these configurations are shown in Figure 6. Both pump and reservoir were located outside the FLAME Facility. With the largest nozzle, the low pressure configuration was capable of delivering pressures of less than 50 psi, and with the smallest nozzle, the high pressure configuration was capable of delivering pressures close to 320 psi. Because of limited capacity of the water pump, tests were limited to pressures less than 320 psi.

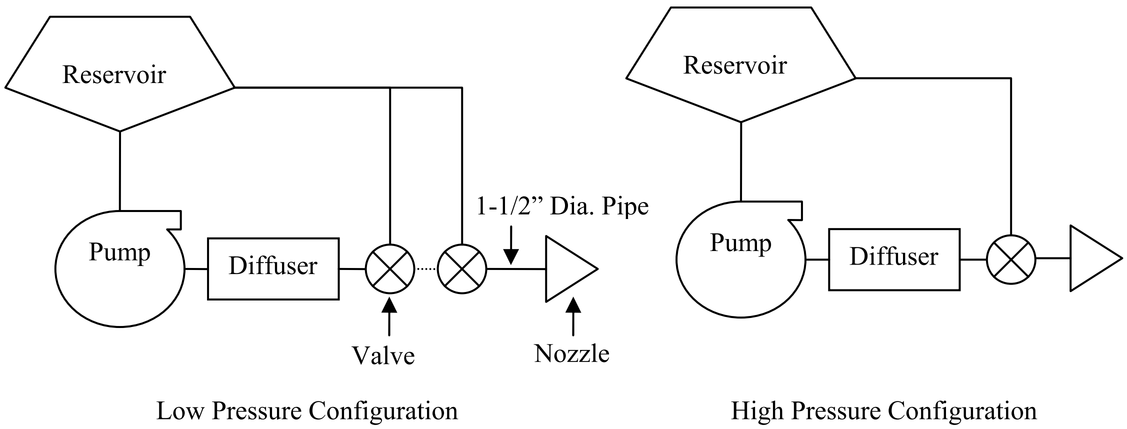
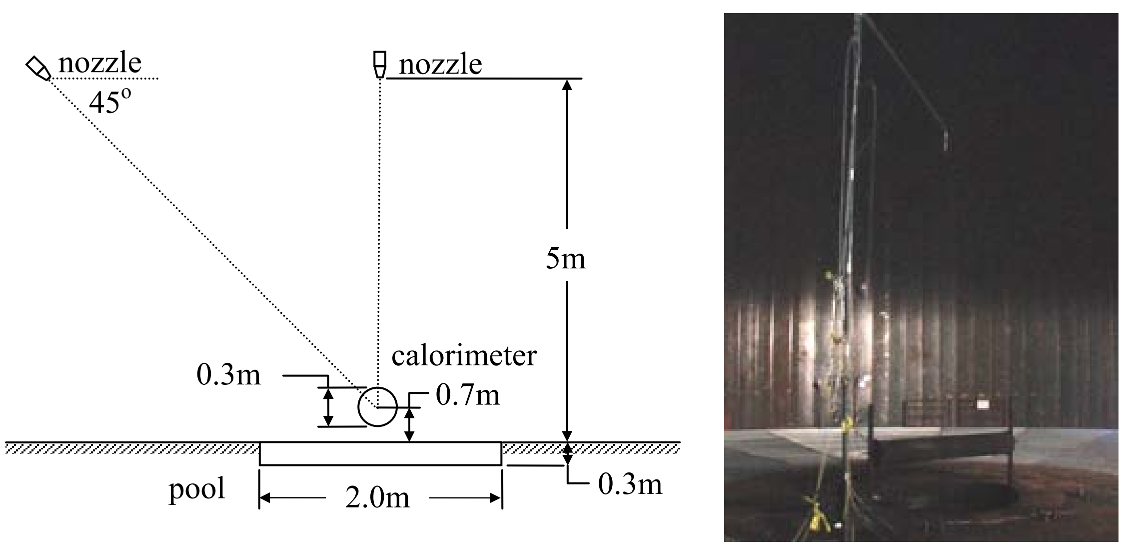


Figure 6. Suppression System Configurations.

Two spray angle configurations were used in these experiments: a 45º and a 90° (see Figure 7). In the 90° configuration the nozzle was positioned directly above the calorimeter



(a) (b)

Figure 7. Nozzle Configurations.

(see Figure 7b), and in the 45° configuration the nozzle was slightly less than 4.0 m from the center of the pan. In both configurations the nozzle was approximately 5 m from the top of the pan.

A calorimeter was used is some experiments to determine the effects of the fire on high consequence assets. The calorimeter was 0.3 m in diameter and was located approximately 0.7 m above the top of the pan.

All tests were conducted using a 2 m diameter pan. The pan was first filled with 1" of water, followed by ½" of JP8 fuel (~12 gallons).

3.3. Nozzles

All nozzles used in these experiments were 30 degree full solid cone (see Figure 8). This type of nozzle gives a uniform, round, full spray (as opposed to a hollow cone) pattern with medium-to-large droplet size. All nozzles were manufactured by Spraying Systems, Co., Wheaton, IL. Nozzle characteristic data (provided by Spraying Systems) is discussed in section 4.

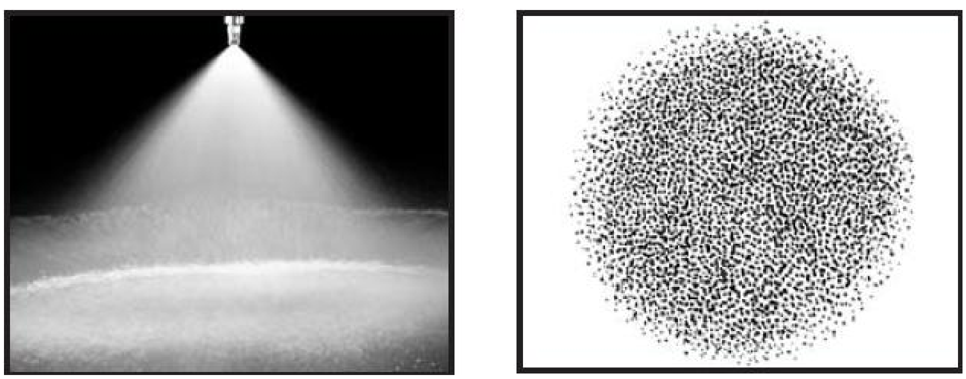


Figure 8. Solid Cone Nozzle Spray Pattern.

Table 1 gives the inventory of nozzles obtained from Spraying Systems, Co. From this table, only nozzles 30200, 30400, 3014, and 3050 (were used in these experiments. The 3014 and the 3050 nozzles arrived late into the testing; due to time constraints, no characteristic spray data was provided for these nozzles.

Table 1 Nozzles obtained from Spraying Systems, Co.

Nozzle Model No.	Nozzle Diameter (in)
30200	0.344
30250	0.375
30300	0.406
30350	0.438
30400	0.469
3014	0.94
3050	0.172

3.4. Test Instrumentation

3.4.1. Water Pressure

A pressure gage was installed on the steel pipe close to the nozzle and was used to determine the pressure at the inlet of the nozzle. This method is consistent with the method employed by the manufacturer to generate the nozzle characteristic data (see section 4).

3.4.2. Heat Flux

The calorimeter was made of stainless steel cylinder 12 inches outside diameter, 16 inches long, with a 1/8 inch wall thickness. The ends were fitted with 0.25 inch thick stainless steel end caps. Intrinsic Type K thermocouples (TCs) were spot welded to the inner surface in four places every 90 degrees. These TCs were located 8 inches from each end and in the center of each end cap. Also included were four sheathed TCs 1 inch from the inside wall adjacent to each intrinsic TC. These sheathed TCs were located at the very center of the inside of the calorimeter to check for shunting and noise (data validation purposes). The inside of the calorimeter was packed with multiple layers of 1 inch thick ceramic fiber insulation. The end plates were bolted to the cylinder ends. All external surfaces were painted with a high-temperature black paint to yield a known emissivity [15] (Pyromark 2500, emissivity = 0.85 ± 0.09).

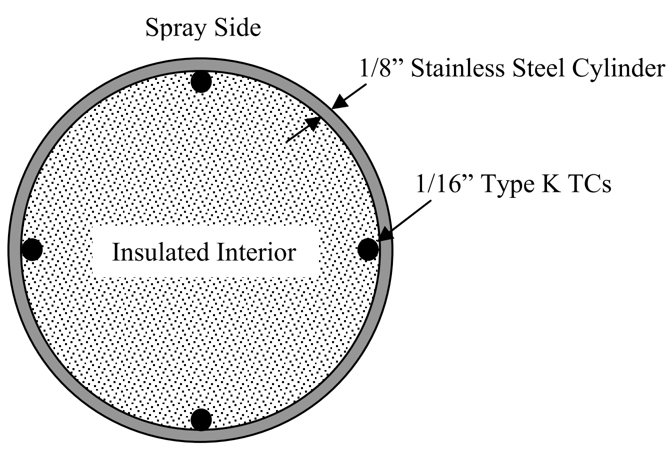


Figure 9. Calorimeter Cross Section at centerline.

3.4.3. Photometric Coverage

Four video cameras (in water-cooled enclosures) were placed at four different locations inside of FLAME. Two cameras recorded normal and parallel views of the fire; a third camera recorded the fire from above; a fourth camera monitored activity below the floor plane to check for spillage and splashing from the fuel pan. As appropriate, the field of view of the three cameras looking at the fire was adjusted prior to the test to encompass the entire height of the continuous flame zone.

3.5. Data Acquisition and Validation

The data acquisition system (DAS) at TTC consists of a PC with a 16-bit data acquisition card connected to a National Instruments (NI) SCXI-1001 chassis. It has twelve NI SCXI-1102 cards with NI SCXI-1303 blocks for TCs and four NI SCXI-1104 cards with NI SCXI-1300 blocks for analog signals. This provides the ability to increase either analog signals or TC signals. Note that the SCXI-1001 presently holds 12 cards, yielding a total channel count of 384 channels if all slots are used for data acquisition. The system is upgradeable simply by adding an additional SCXI-1001 DAQ card and more multiplexer units (MUXs).

The data acquisition system can acquire temperature, heat flux, and pressure data. The integrity of all thermocouple channels is evaluated prior to each experiment with an Ectron thermocouple simulator, which inputs a controlled signal into each channel at the thermocouple device connection point and provides a check on the integrity of the channel hardware and software from that point to the final magnetic storage location.

Data are sampled simultaneously for all channels, typically at 1000 Hz with an average value recorded at a rate of at least one sample per second, starting at least two minutes prior to the fuel ignition and continuing after burnout of the fire.

A formal checklist for conducting the test is created and used to record actions during the test event. The data from the instrumentation are organized via a Data Channel Summary Sheet and with sketches showing instrumentation location. This summary sheet contains a channel-by-channel listing of the instrumentation with details such as expected range, sampling rate, calibration date and source, instrument location, and the data sample rate. Post-test, all data are collected and converted to electronic format for purposes of archiving and dissemination via PC media (i.e., CD or equivalent).

3.6. Experiment Procedure

The general procedure for the conduct of these tests was very simple and straight forward. Approximately ½" of JP-8 fuel was poured on top of the water in the 2 m pan (nominally providing about a 3 minute fire). The forced draft fan was energized and set to maintain an air flow rate of 150,000 scfm. After the fire was fully developed (1-2 minutes) the fire suppression system was activated. If the fire was extinguished, the suppression system was deactivated shortly there after. If the fire was not extinguished after about 30-40 seconds, the suppression system was turned off.

For each test in the series the following general procedure was to be followed:

1. Desired nozzle was installed.
2. If the calorimeter was used, it was installed above and at the center of the pan.
3. The tip of the nozzle was located with respect to the center of the pan or the calorimeter, depending on which configuration was used (45 degree or 90 degree).
4. The suppression system was briefly activated to make sure the water spray covered the fuel pan.
5. JP-8 fuel was introduced to the pan.
6. The data acquisition and VCR cameras were started.
7. The fuel was ignited

4. Nozzle Characterization

A Phase Doppler Particle Analyzer (PDPA) was used to obtained droplet volume diameter and droplet velocity (see Figure 10). These data (from Spraying Systems, Co.) were taken 1 m from the exit of the nozzle, at three different locations along the diameter of the nozzle spray starting from the center (i.e., 0.0, 0.1 and 0.2 m). The complete data set is given in Appendix B; in this section we summarize the results.

Spraying Systems, Co. also provided pressure-flow rate characteristic curves. The pressure was measured approximately 0.3 m from the exit of the nozzle.

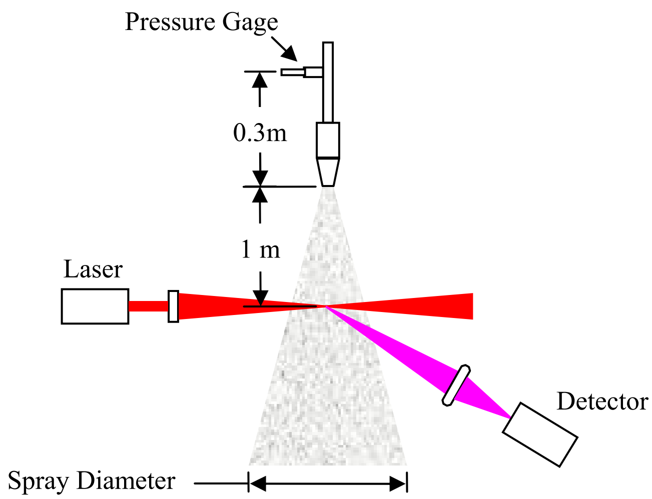


Figure 10. Droplet Size and Velocity Measurement System.

4.1. Droplet Diameter and Velocity Characteristics

The results shown in this section pertains to nozzles 30200 through 30400. Nozzles 3014 (0.94") and 3050 (0.172") were not tested prior to experiment, so they are not included in the figures below (For more details, see comments in section 3.3).

Figure 11 and Figure 12 show the droplet volume mean diameters and velocities, respectively, for the characterized nozzles. The Volume Mean Diameter (VMD), D0.5, is a means of expressing droplet size in terms of the volume of liquid sprayed. The VMD is a value where 50% of the total volume (or mass) of liquid sprayed is made up of droplets with diameters larger than the mean value and 50% smaller than the mean value. Note that the pressure is directly proportional to the injection velocity of the nozzle. Hence, the correlation of the mean diameter and injection velocity can be deduced from Figure 11. As expected, the mean diameter decreases as the injection velocity increases. The reason for this behavior is attributed to the fact that the turbulent Kolmogrov lengths scale decreases as the Weber number or Reynolds number decreases; the droplet size naturally reduces in response of the reduced dominant length scale.

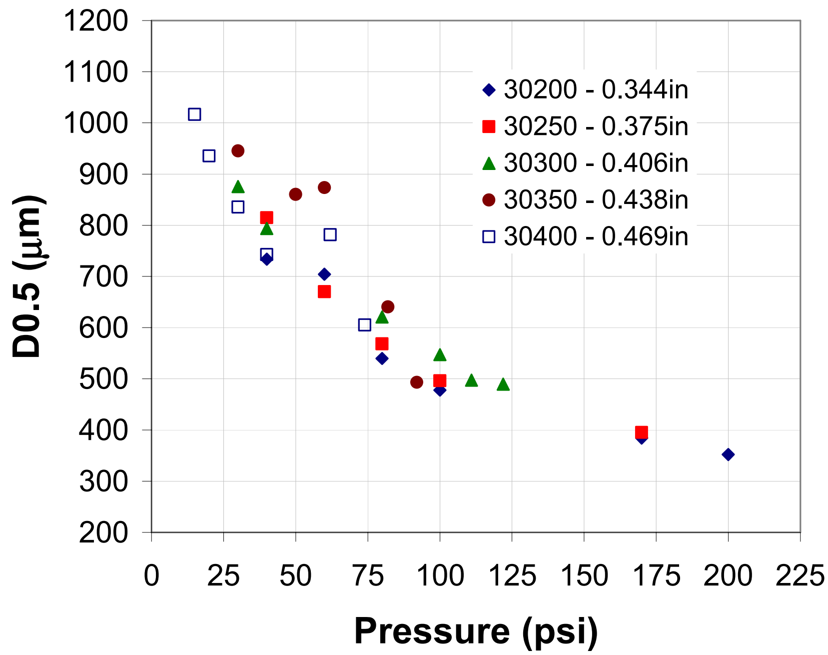


Figure 11. Correlation Between Droplet Mean Diameter (D0.5) and Pressure.

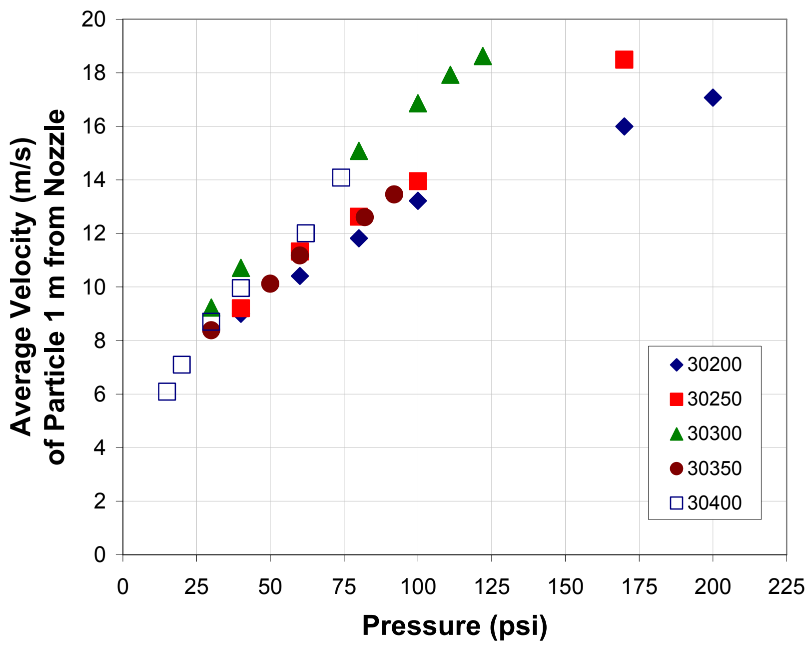


Figure 12. Correlation Between Spray Velocity and Pressure.

Again, the mean velocity of the droplets was measured 1 m away from the nozzle exit. It should be noted that the injection velocity of the droplets at the nozzle exit is generally higher than the velocity range shown in Figure 12. The air drag reduces the droplets initial velocity as the droplets are traveling.

Note these results show there is no significant difference in droplet diameter between nozzle models.

4.2. Nozzle Flow Rate-Pressure Characteristics

Figure 13 shows flow rate-pressure characteristic curves for nozzles obtained from Spraying Systems. Note the same flow rates can be achieved with several nozzles because the operating pressure can be varied. It should be kept in mind, however, that the same flow rate does not necessarily yield the same suppression performance because nozzle characteristics (i.e., droplet size and velocity) vary with nozzle diameter. Note the relatively small differences observed between the performance curves for nozzles 30250, 30300, 30350 and 30400 at high flow rates. For this reason, only nozzles 30200 and 30400 were used in the high flow rate experiments. Both low flow rates nozzles, 3014 and 3050, were used in the experiments. The curve fits for the nozzles used in the experiments are also shown in Figure 13.

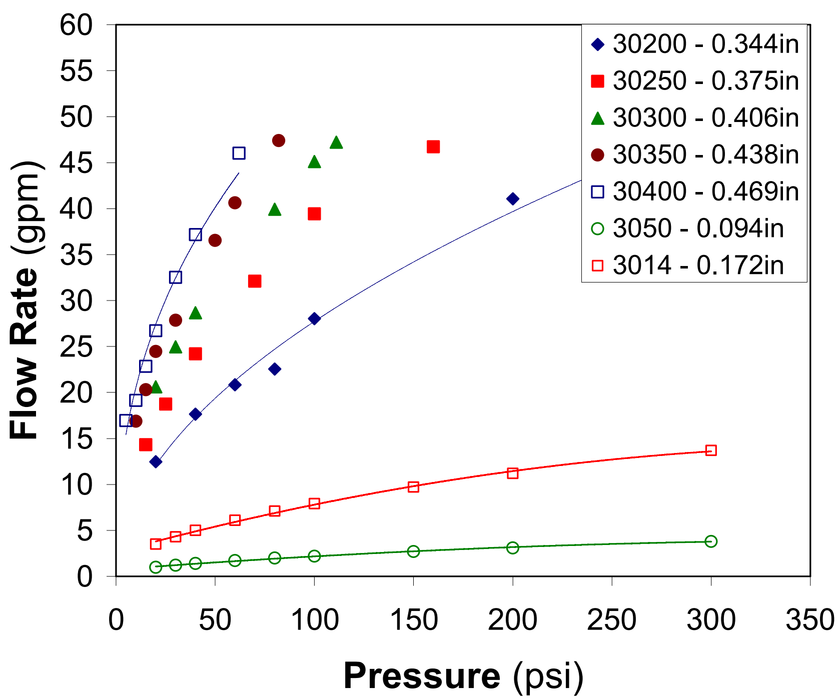


Figure 13. Nozzle Flow Rate-Pressure Characteristic Curves.

5. Suppression Tests Results and Analysis

A total of 12 fire suppression benchmark test *cases* (48 total *experiments*) were conducted in the new FLAME facility. The following parameters were varied in these tests:

1. the position of the spray injection (45 and 90 degree injection angle),
2. operating pressures, and
3. the existence of the calorimeter directly above the pool fire.

Tables 2 and 3 show test runs for 90 and 45 degree nozzle angles, respectively. Two test runs were performed for each test, one with and one without a calorimeter. In addition, each test run was repeated twice to test repeatability of results. Results showed that while the 90 degree test cases were repeatable, the 45 degree test cases were not in all cases.

Table 2 Test Cases for 90 degree angle

Test No.	Operation Pressure (psi)	Flow Rate (gpm)	Nozzle Model No./ Diameter (in)
1	52	42	30400/0.469
2	74	48	30400/0.469
3	190	39	30200/0.344
4	25	14	30200/0.344
5	100	28	30200/0.344
6	155	34	30200/0.344
7	317	4	3050/0.094
8	317	14	3014/0.172

Table 3 Test Cases for 45 degree angle

Test No.	Operation Pressure (psi)	Flow Rate (gpm)	Nozzle Model No./ Diameter (in)
1	25	14	30200/0.344
2	100	27	30200/0.344
3	155	34	30200/0.344
4	190	39	30200/0.344

5.1. 90 Degree Injection Angle

Figure 14 summarizes results of suppression tests with the 90 degree nozzle configuration. The arrows in the figure point to the operating conditions of the test run. The labels “Supp” and “No Supp” in the figure indicate the operating conditions where suppression was achieved or not achieved, respectively, whether the calorimeter was present or not. The label “Supp only for w/o calo” indicates suppression was achieved only for the case without the calorimeter. Suppression occurs when fire is fully extinguished.

As Figure 14 shows, for a single nozzle, suppression was achieved when the operating flow rates and pressures where on the high end of the nozzle operating curve. For example, in the case of nozzle 30200 (0.344 in nozzle diameter), suppression was not achieved with and without the calorimeter when the flow rate was 14 gpm (see Test 4). For the same nozzle, suppression was achieved without the calorimeter when the flow rate was 28 gpm (Test 5). Finally, for the same nozzle, suppression was achieved with and without calorimeter at greater flow rates (Test 6 and Test 3).

Similar trends were observed with nozzle 30400 (0.469 in nozzle diameter), although at different operating conditions and in only two tests. In the case of nozzle 3014 (0.172 in nozzle diameter), suppression was achieved without the calorimeter at 14 gpm, the highest flow rate the suppression system could operate with this nozzle. For nozzle 3050 (0.094 in nozzle diameter), suppression was not achieved with and without the calorimeter. Due to the limitations of suppression system, the highest flow possible with nozzle 3050 was 4 gpm.

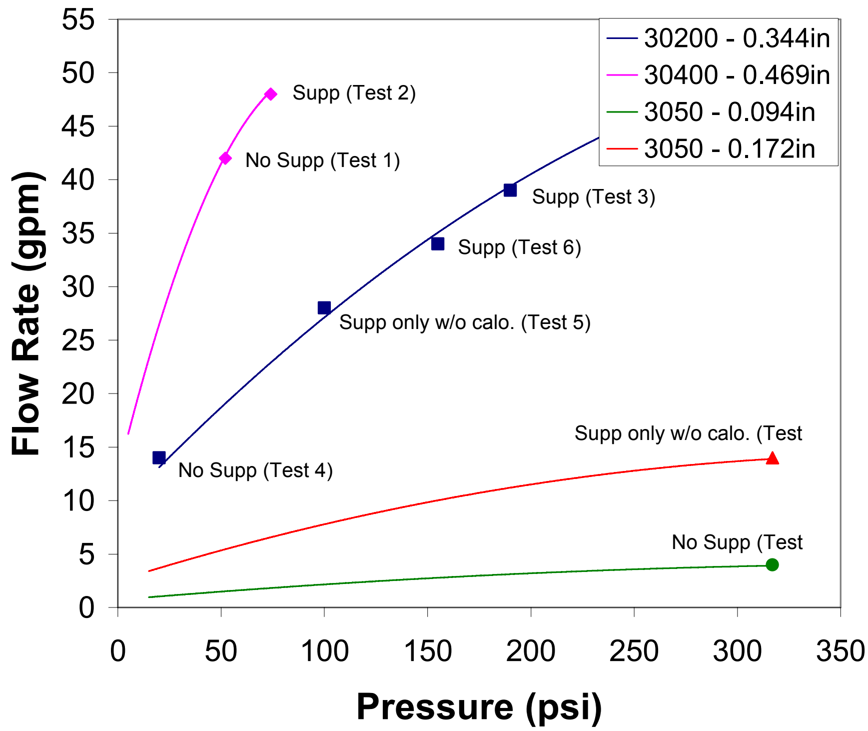


Figure 14. Summary Results of the Suppression Tests.

Figure 15 shows the time series snapshot of the fire suppression conducted with nozzle 30200 under a 28 gpm flow rate without the calorimeter. The image taken at t=-0.333sec shows a typical fire prior to the spray injection—fires never remains the same due to the nature of large scale turbulent structures. The image taken at t=0.000sec shows the fire structure when the water spray was initially injected (see the frame No. 2 in Figure 13). Figure 15 shows the fire was suppressed when the calorimeter was not present. Here, the suppression time is defined as the time at which the fire is not visible in the images. In reality the fire was extinguished near the fuel surface at a slightly earlier time even though flames remained visible in the upper region of the fire.

Notice that when the spray reached the flame, the fire intensity increased, increasing the heat flux emitted to the vicinity of the fire (see the images from t=0.33sec to t=1.67sec). The increase in fire intensity is believed to be caused by an enhanced fuel mixing rate. In this case the spray momentum was sufficiently high to reach the fuel surface; therefore, suppression was achieved. A rough estimate of an individual droplet momentum (i.e., $\sim\rho_{H_2O}(\pi/6)D_{0.5}^3V_{1m}$, where $D_{0.5}$ is the droplet diameter and V_{1m} is the droplet velocity) gives 8.83 X 10^{-7} kg m/s ($D_{0.5}$~ 500 µm and V_{1m} ~ 13.5 m/s, see Figure 11 and 12), 1 m downstream from the nozzle exit. The total momentum can be obtained by summing the droplet momentum over the total number of water droplets.

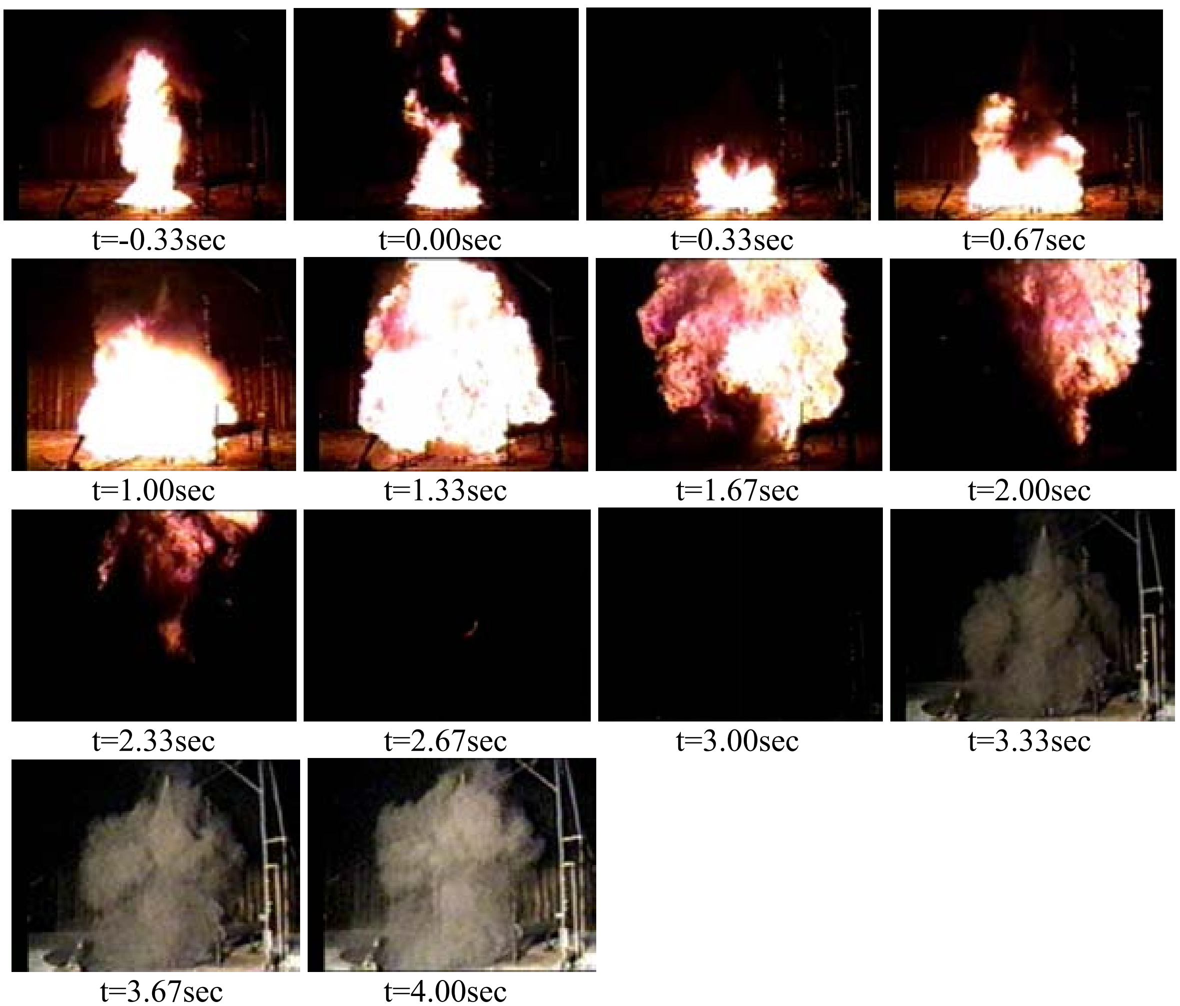


Figure 15. 90° Spray at 100 psi (28 gpm) *Without* the Calorimeter (Test 5).
(Suppression is achieved approximately at 3±1/3sec.)

Figure 16 shows the time series snapshots of the fire suppression conducted with nozzle 30200 injecting at a constant flow rate of 28 gpm and using the calorimeter. Again, the image taken at t=-0.333 sec shows the typical fire structure prior to the spray injection, and the image taken at t=0.000 sec shows the fire structure when the water spray was initially injected. In this case the fire is not fully suppressed (extinguished) even though the nozzle's operating condition is the same as in the previous case. In general, the presence of the calorimeter yielded more difficult condition to suppress the fire.

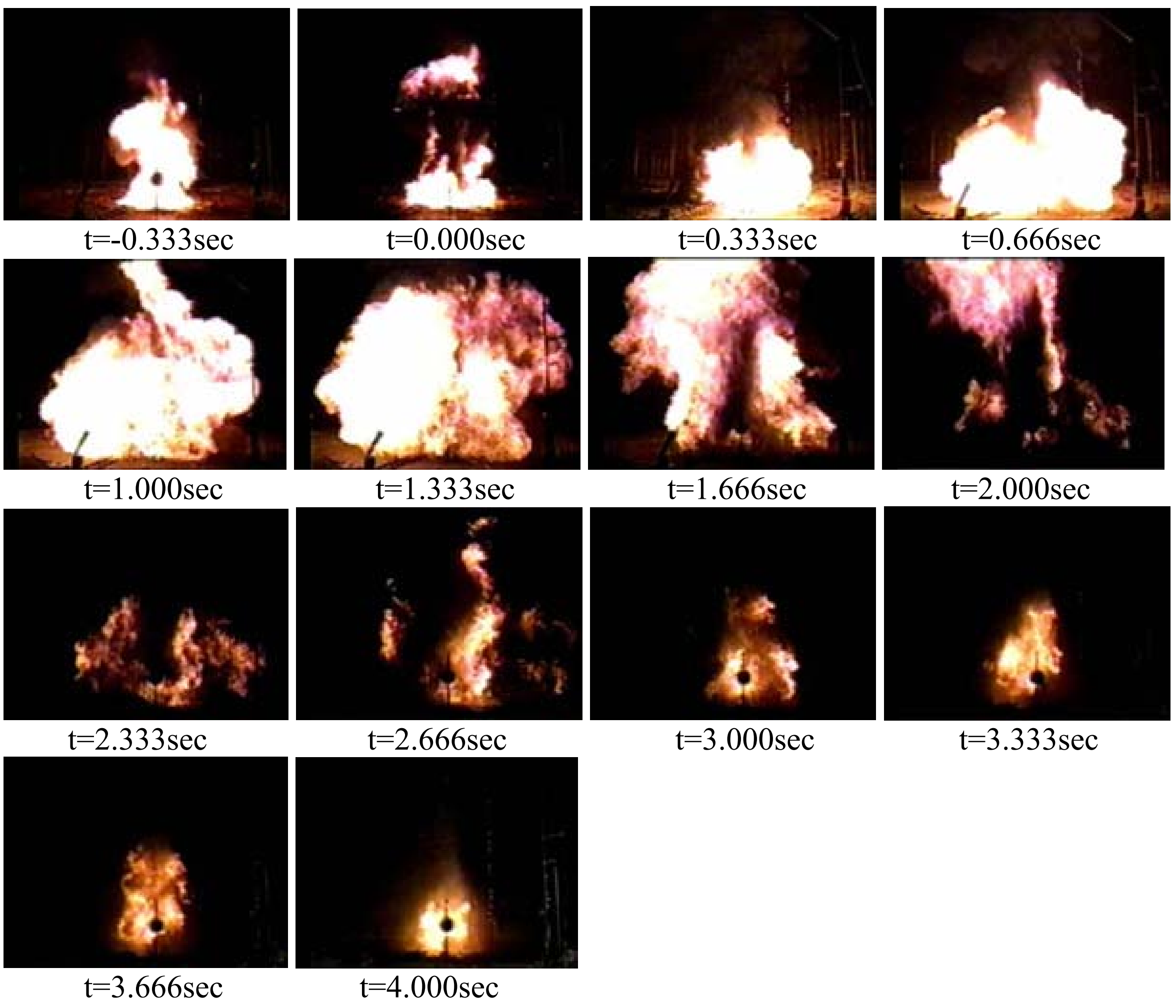


Figure 16. 90° Spray at 100 psi (28 gpm) *With* the Calorimeter (Test 5).
(Extinguishment is never achieved.)

Notice again that when the spray reached the flame, the fire intensity increased (see the images from t=0.333 sec to t=1.666 sec). Judging from the images in Figure 16 and Figure 16 and the operating conditions, the enhanced fire intensity is comparable in both cases. This observation indicates that the enhanced fire intensity may be proportional to the total momentum of the injected water spray. Note also that fire intensity below the calorimeter increases due to enhance mixing produce by the presence of the calorimeter.

Figure 17 shows the time series snapshot of the fire suppression conducted with nozzle 30200 and the calorimeter under the 34 gpm injection pressure. In this case, the fire was fully suppressed even with the calorimeter present (t=1.67±1/3 sec). In this case the momentum of the spray did not enhance the fire intensity.

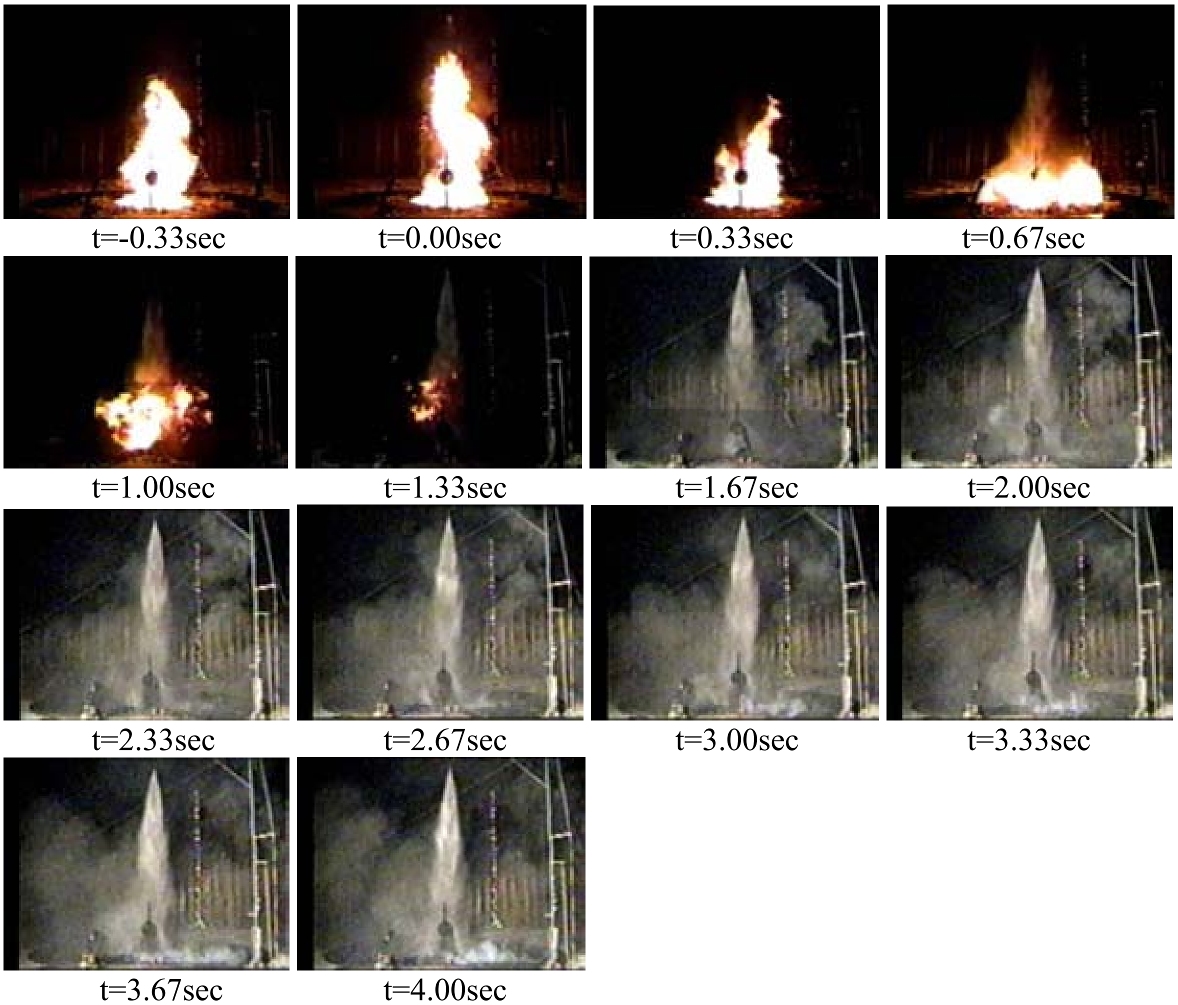


Figure 17. 90° Spray at 155 psi (34 gpm) *With* the Calorimeter (Test 6).
(Extinguishment is achieved approximately at 1.67±1/3sec.)

At 34 gpm, the mean droplet diameter and velocity were estimated to be 400 μm and 14 m/s, respectively, 1 m downstream from the nozzle exit. A rough estimate of the individual droplet momentum gives 4.69 x 10^{-7} kg m/s. This value is actually smaller than the one estimated for nozzle 30200 at 100 psi (8.83 X 10^{-7} kg m/s) even though the velocity of the droplet is higher. Individual droplet momentum is more sensitive to the change in droplet size, since it is proportional to $D_{0.5}^3 V_{1m}$. Realize, however, that the number of droplets has increased due to the increase in flow rate; therefore, the total momentum of the spray has increased.

Figure 18 shows the time series snapshot of the fire suppression conducted with nozzle 30200 injecting at 39 gpm without a calorimeter below. The snapshots in Figure 18 show the flame intensity was enhanced slightly more with an even higher spray momentum. Suppression was achieved at about t_s=2.67 sec. This suppression time is longer than the 34 gpm case (t_s=1.67 sec) and is comparable to that of the 28 gpm case without the calorimeter (t_s=2.67 sec).

Figure 19 shows the time series of the suppression system over pool fire with nozzle 30200 injecting at 39 gpm with a calorimeter below. In this case suppression was achieved at a slightly later time (t_s=3.00 sec) than when the nozzle was operating at 34 gpm with the calorimeter in place (compare Figure 17 and 19). Flame intensity was also enhanced in this case and is comparable to the case without the calorimeter (see Figure 18).

Initially, it was thought that increasing overall spray momentum with greater flow rate was desirable to achieve an efficient suppression. However, Figures 17 through 19 indicate that the relatively smaller momentum of the spray (as depicted in Figures 17) is more suitable to prevent any unwanted flame intensification. Thus, increasing momentum is favorable only up to a certain limit, which we refer to as optimum flow rate. Any flow rate exceeding the optimum value would intensify the flame.

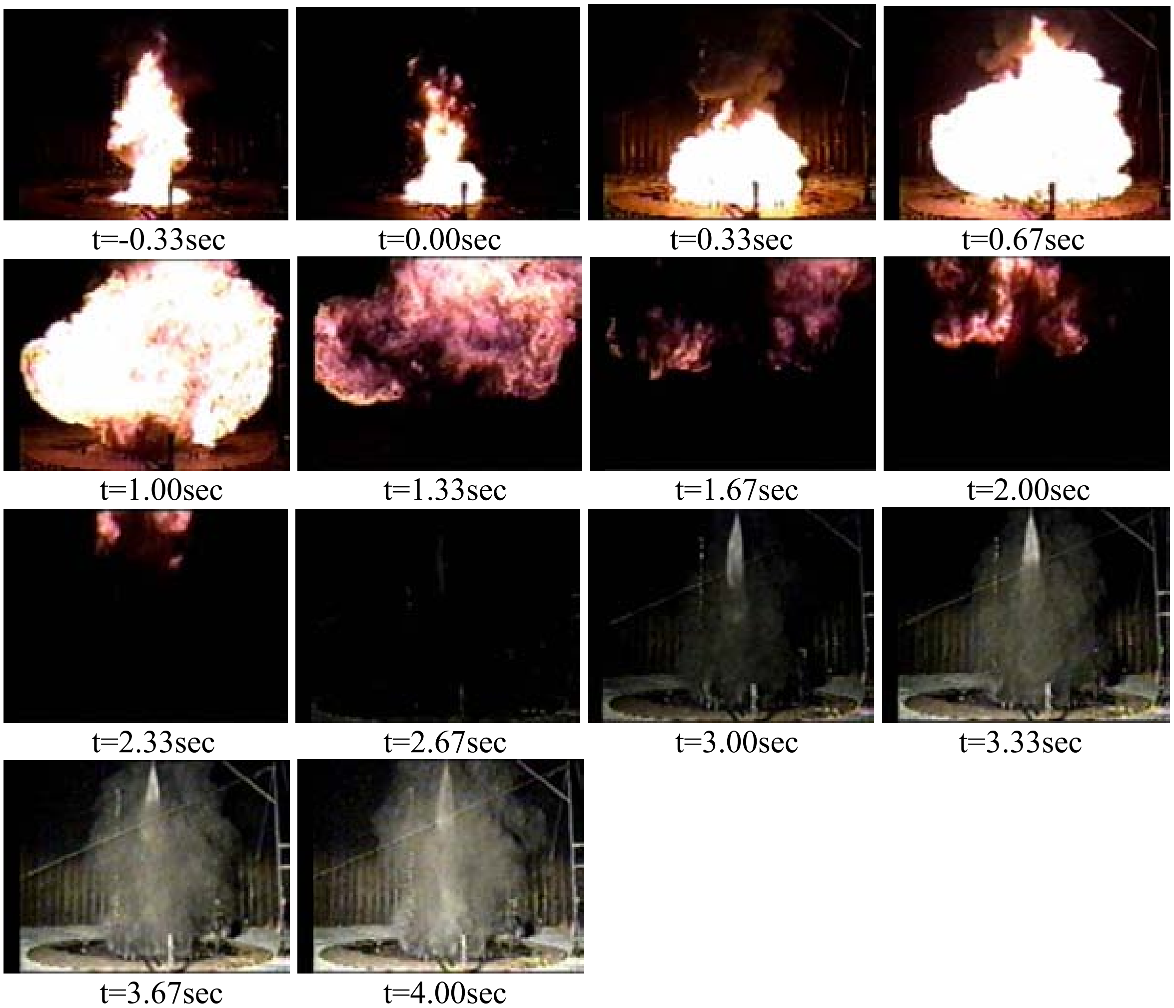


Figure 18. 90° Spray at 190 psi (39 gpm) *Without* the Calorimeter (Test 3).
(Extinguishment is achieved approximately at 2.67±1/3sec.)

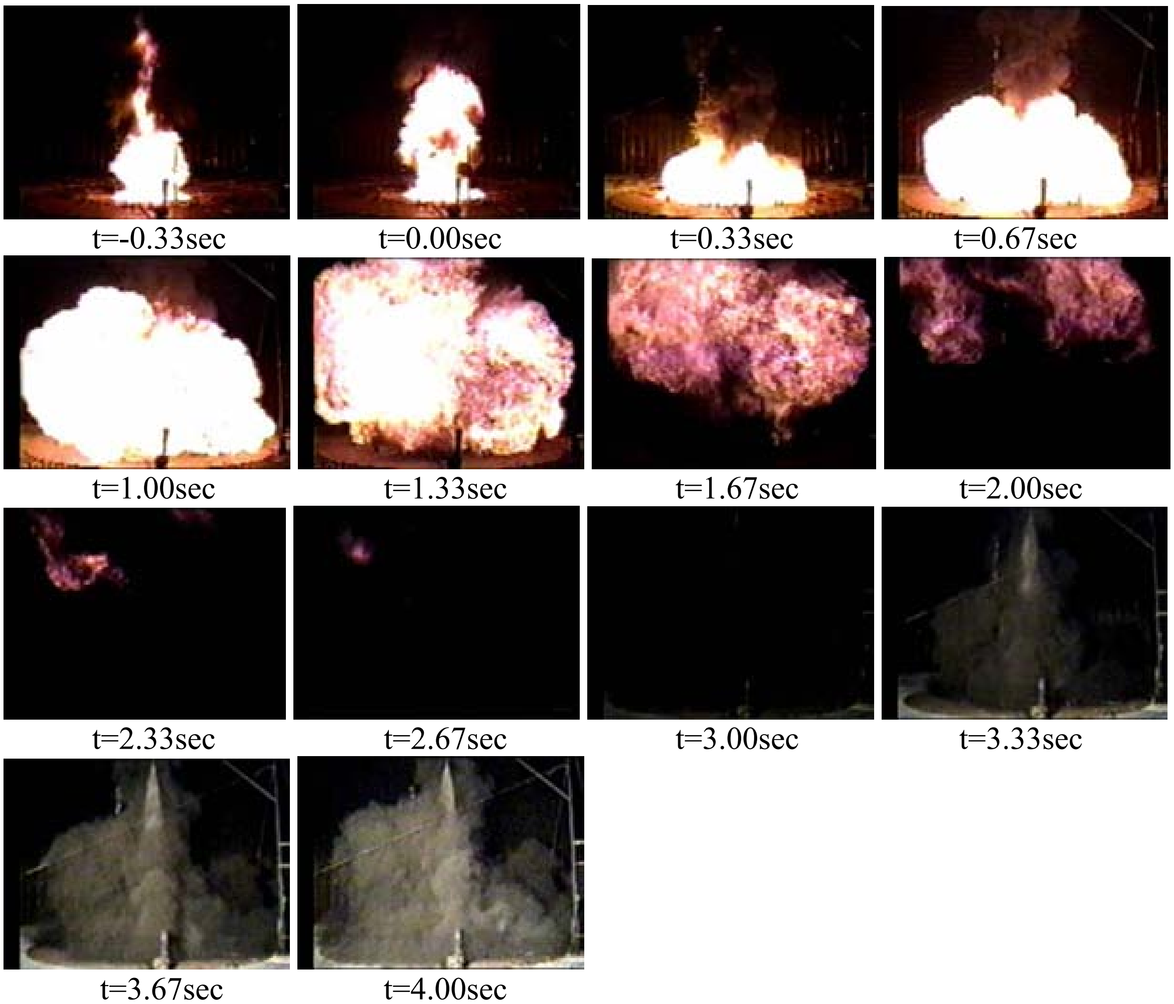


Figure 19. 90° Spray at 190 psi (39 gpm) *With* the Calorimeter (Test 3).
(Extinguishment is achieved approximately at 3±1/3sec.)

Based on the aforementioned experiments, a rough critical line was constructed as shown in Figure 20. This line is defined as the point at which the suppression is achieved without the calorimeter. In other words, any operating regime below the critical line will not yield a suppression condition and any operating regime above the line will guarantee suppression for the case without the calorimeter. To guarantee suppression for the case with the calorimeter, a certain marginal tolerance - shifting to upper right regime with respect to the critical line in Figure 20 - needs to be considered. This tolerance should be estimated based on the experimental data.

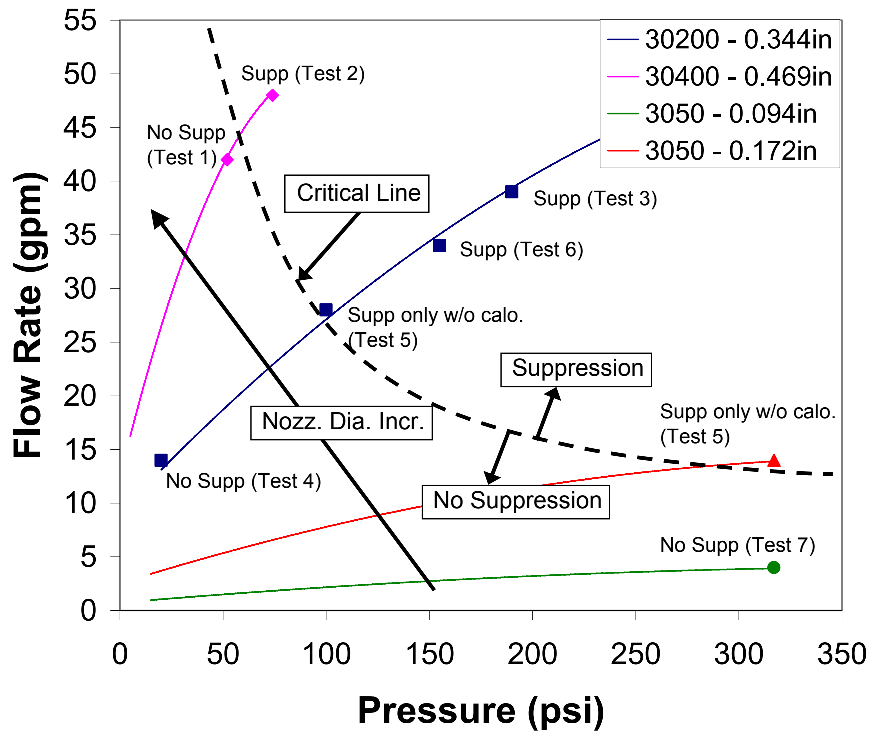


Figure 20. Critical Line for Suppression for 90 Degree Spray Injection.

5.1.1. Calorimeter Incident Heat Flux

Calorimeter temperature data were post-processed to obtain temporally-resolved estimates of heat transfer to the surface of the calorimeter based on the heat flux gauge (HFG) data reduction methodology described in Blanchat et al. [16]. As illustrated in Figure 9, four thermocouples were used to measure the distribution of an idealized one-dimensional heat flux to the exterior surface calorimeter (see section 3.4.2 for a more detail description of calorimeter).

The heat balance on the heated surface of an idealized one-dimensional heat flux calorimeter can be summarized by the following equation:

$$\alpha\, q_{surf}(t) = \varepsilon\, q_{rad}(t) + q_{steel}(t) + q_{insul}(t) + q_{conv}(t)$$

where $q_{surf}(t)$ is the heat flux incident to the calorimeter, $q_{rad}(t)$ represents the heat re-radiated from the surface of the calorimeter, $q_{steel}(t)$ is the heat stored through the thickness of the calorimeter, $q_{insul}(t)$ is the heat loss to the insulating material (Kaowool), and $q_{conv}(t)$ is the convective heat loss.

The convective heat component of the incident heat flux, $q_{conv}(t)$, was not considered in the data reduction. This component can be estimated using convection coefficient correlations, the calorimeter temperature and the free stream gas temperature. Far from the fire, the convection coefficient over a flat horizontal plate is expected to be less than 30 W/m^2-K. This value is based on: (1) a free stream air velocity of 5 m/s and a temperature of 500°C (mean of ambient and HFG TC temperature), (2) convection coefficient correlations for forced convection of air over a flat plate, and (3) assuming turbulent flow over the entire HFG plate. The convection coefficient will be much lower for calm wind conditions. Inside large pool fires, vertical gas velocities typically ranged from 5-10 m/s between 2 and 10 m above the pool, and gas temperatures range between 1300K and 1700K depending on wind conditions [17]. Based on this velocity and temperature range, the convection coefficient over a flat horizontal plate is also expected to be less than 30 W/m^2-K. The temperature of the plate can be assumed to be the temperature of the HFG thermocouple.

The convective heat component can be estimated using the convective coefficients and temperature estimates cited above. However, since the level of uncertainty in these estimates is high due to lack of measurements, the convection heat transfer was treated as an uncertainty of incident heat flux calculations. Uncertainty estimates for HFG measurements are given in [17] and include uncertainty due to lack of knowledge of convective heat transfer coefficient, free stream gas temperature, and calorimeter temperature. For typical large pool fires, incident heat flux measurement uncertainty is approximately ±20-40% of the calculated incident heat flux using method in [17]. This estimate was obtained using large pool fire experiment data and is only valid for steady-state conditions. For transient conditions, the uncertainty is expected to be higher.

Incident heat fluxes for the case nozzle 30200 ejecting water at 28 gpm and with calorimeter are shown in Figure 21. Thermocouples were placed at the calorimeter centerline surface at four different positions (i.e., top, bottom, left, and right). Positive and negative heat flux indicates heat gain and loss, respectively. The maximum heat flux recorded was 165 kW/m^2. The heat flux data showed no sign of symmetry when observing the heat flux data from the left and right locations, the behavior of which seems quite natural for the fairly large scale turbulent fire.

At about t=85 sec, the calorimeter at all four locations reached nearly the same temperature, right before the water spray was injected onto the calorimeter at t=90 sec. While the heat flux at all sides of the calorimeter decreases upon water spraying, the spray impinged side of the calorimeter (i.e., North or Nozzle Side), experienced the most sudden cooling due to the heat taken by the evaporating droplets at the calorimeter surface.

The heat flux to the calorimeter was greatly reduced during the duration of the water spray. The heat flux briefly increased after the spray was turned off (t~135 sec) until the remaining fuel was consumed.

Figure 22 shows that with an increase in spray flow rate from 28 gpm to 34 gpm, the spray (commenced at about t=82 sec) suppressed the fire within a short period of time, reaching to zero heat flux state where no heat gain or loss was observed.

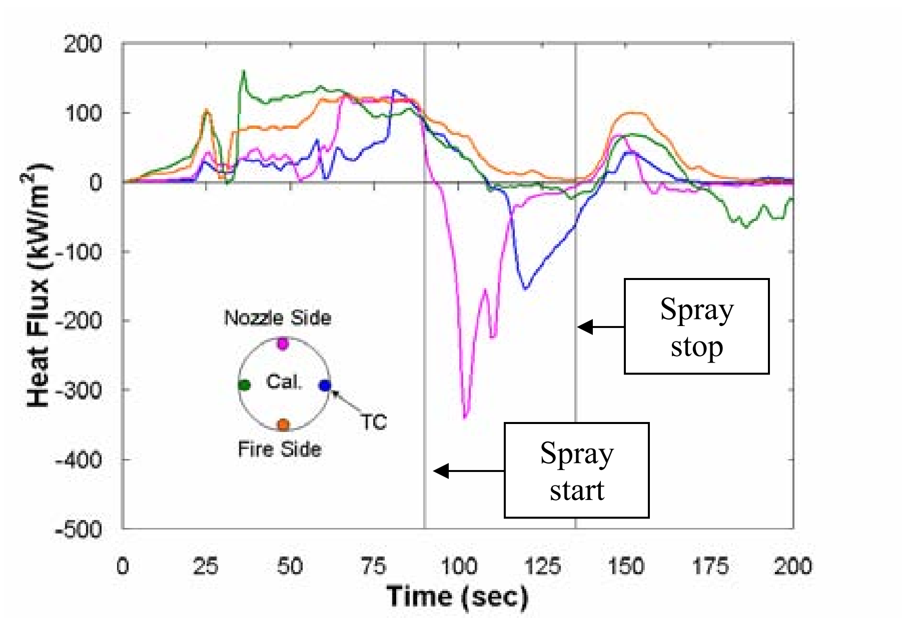


Figure 21. Heat Flux for 90° Spray (100 psi, 28 gpm) with Calorimeter (Test 5).

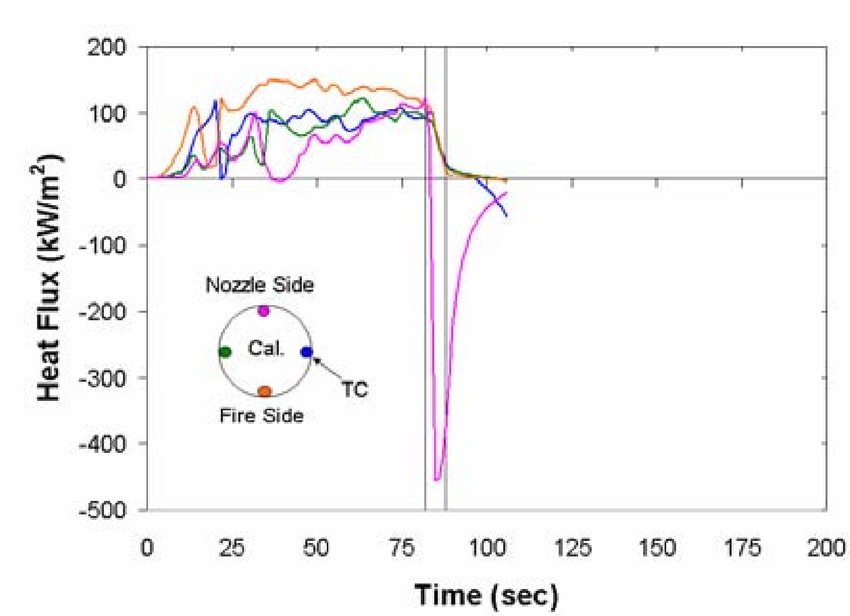


Figure 22. Heat Flux for 90° Spray (155 psi, 34 gpm) with Calorimeter (Test 6).

5.2. 45 Degree Injection Angle

The objective of the suppression tests with a 45 degree injection angle was to seek a nozzle configuration which may yield a better suppression performance.

With the given cone angle of the spray (θ=30^o), the 0.344 inch (diameter) nozzle was configured so that the entire pool fire was covered under the spray impingement area. The height of the nozzle remained same as the previous 90 degree configuration and, thus, the spray travel distance to the calorimeter and the pool fire was increased by the factor of $\sqrt{2}$. The operating pressure was initially set at 25 psi and increased up to 190 psi.

Figure 23 summarizes the test results conducted with the 45 degree spray angle. Suppression was consistently achieved when the operating pressure was greater than 190 psi only for the case without the calorimeter. The fire was suppressed at 155 psi without the calorimeter and 190 with the calorimeter, but these results were not repeatable. In the case at 190 psi without the calorimeter, the suppression time reached nearly 10 times the suppression time of the case with 90 degree injection angle. It is uncertain how high the operating pressure should be to suppress the fire consistently with the calorimeter in place.

Figure 24 and 25 shows the time series snapshots of the fire suppression conducted with nozzle 30200 at 45 degrees injecting at 39 gpm, with and without a calorimeter, respectively. Notice that in both figures the initial fire ball that was observed in the 90 degree angle tests is not present. The fire is enhanced; however, the region of influence is much smaller and lasts for the duration of the test.

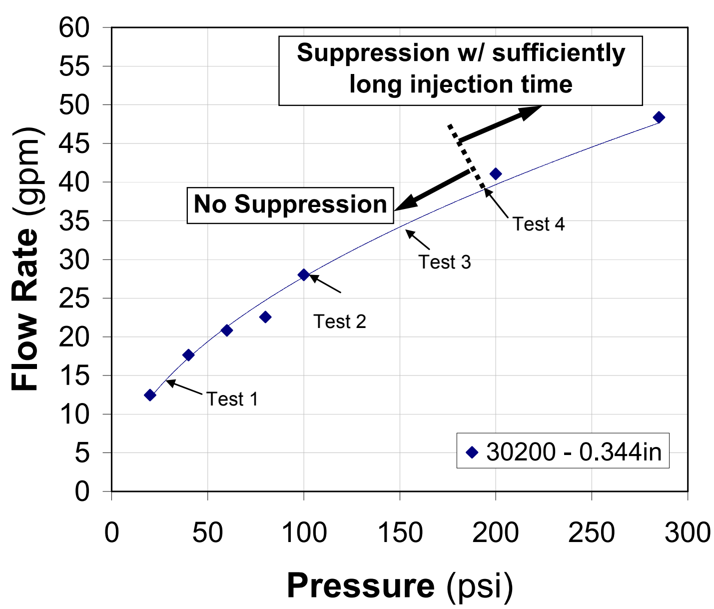


Figure 23. Critical Line for Suppression for 45° Spray Injection.

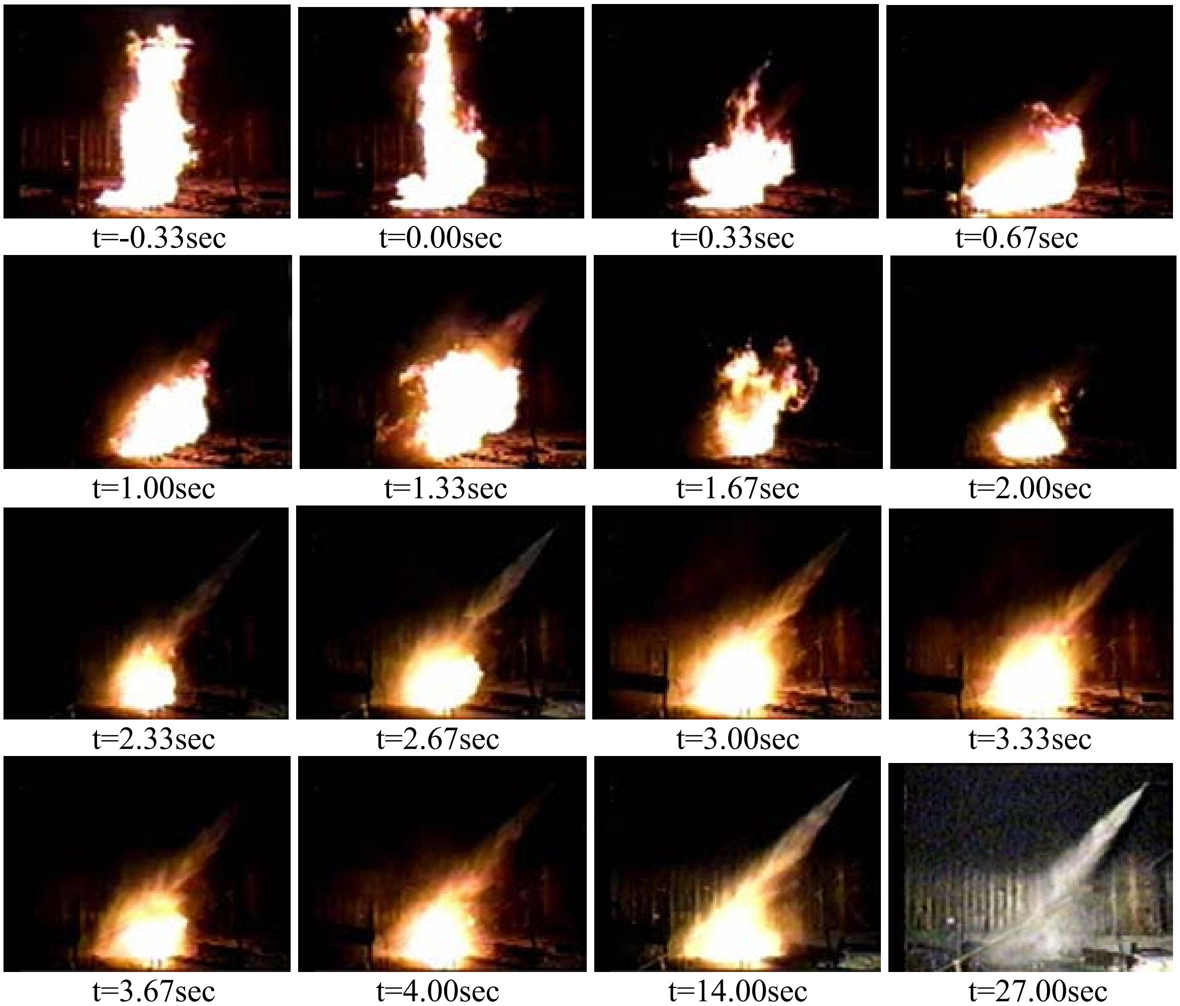


Figure 24. 45° Spray at 190 psi *Without* the Calorimeter (Test 4).
(Extinguishment is achieved at t=27±1/3sec.)

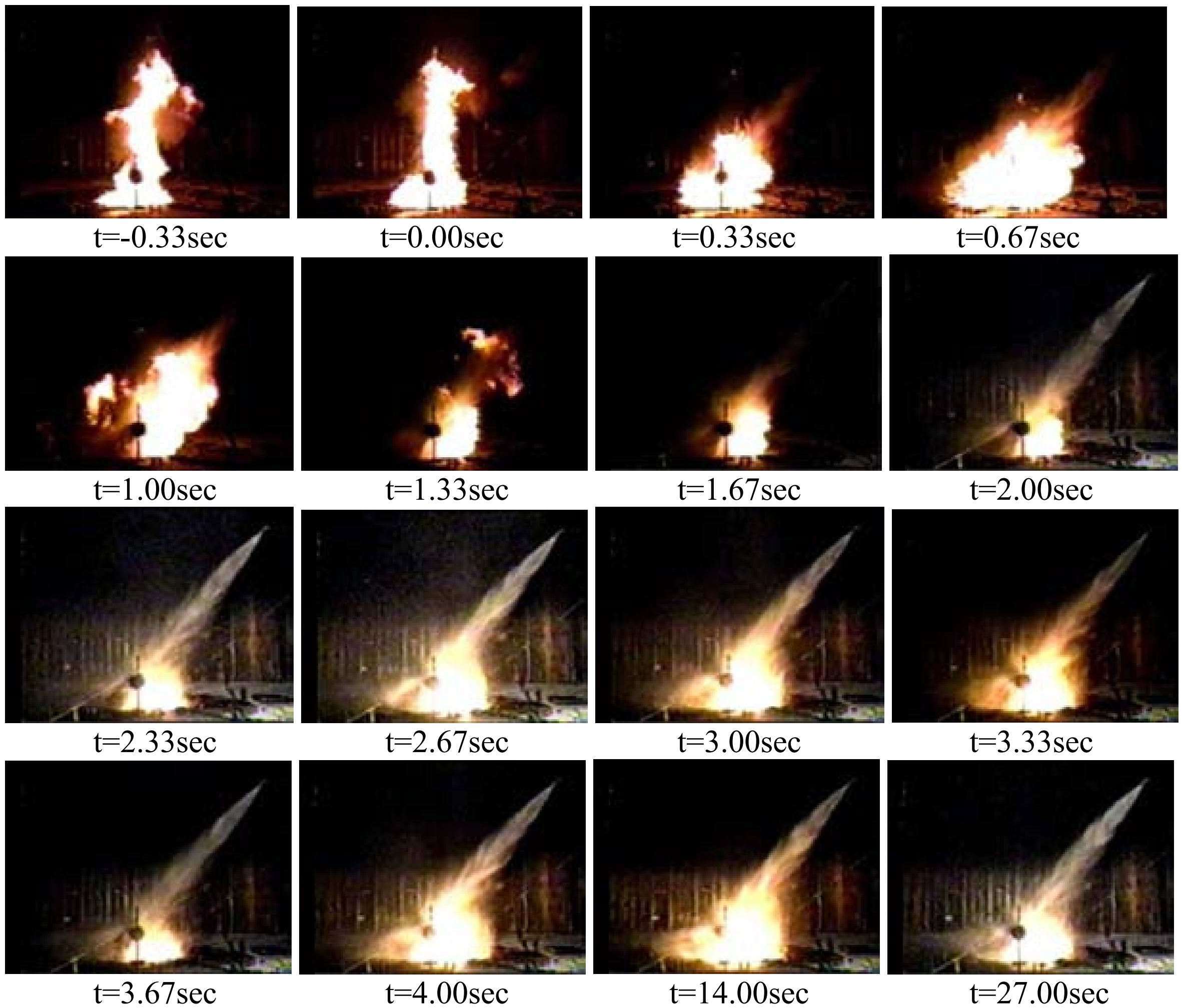


Figure 25. 45° Spray at 190 psi *With* the Calorimeter (Test 4).
(Extinguishment is never achieved.)

The reason for poor performance of the 45 degree nozzle configuration is attributed to the several factors. First, the spray travel distance was relatively long with the 45 degree nozzle; see Figure 26. The momentum of the spray can be quickly reduced, especially when the spray droplets see a strong flame field counter flow. Second, the spray was unevenly distributed across the fire, stirring the fire and enhancing the mixing rate. As a result, the fire became difficult to suppress.

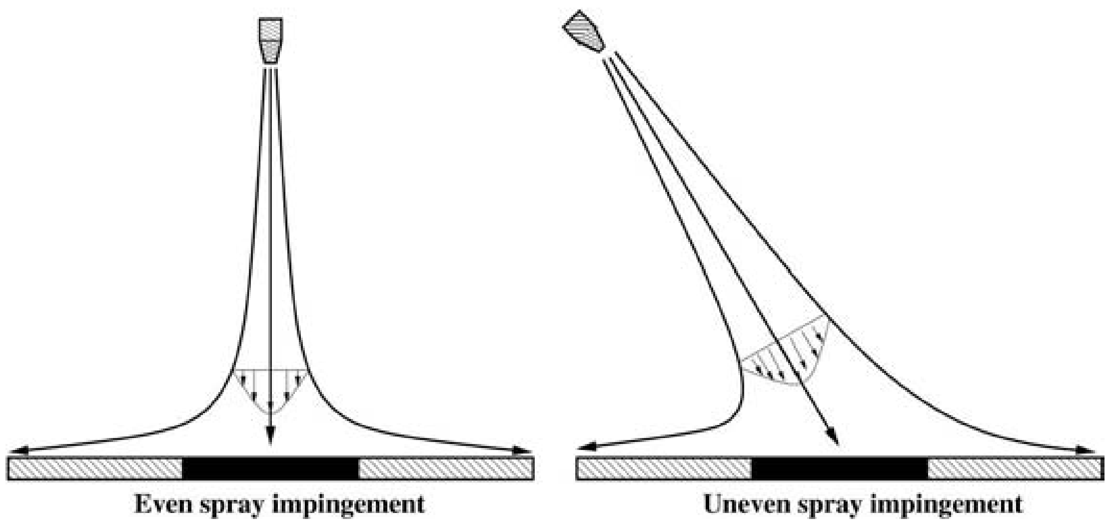


Figure 26. Schematic for 90° and 45° spray impingement angles.

6. Conclusions

The objective of this work was to complete a series of new fire benchmark tests which explored modern fire suppressant agent dispersal systems and new suppressants that may be used for the protection of high value assets. The results of the testing were to provide boundary and temporal data to match the necessary inputs for model development and validation efforts for the evaluation of the SNL fire physics codes, VULCAN and FUEGO.

In the Phase 1 test series, the benchmark experiments were limited to one fuel (JP-8) and to only one type of suppressing agent (water). A total of twelve test configurations (48 total tests) were conducted to characterize water mist suppression technology: eight with the 90 degree spray angle configuration and four with the 45 degree spray angle configuration. Two test runs were performed for each test, one with and one without a calorimeter. In addition, each test run was repeated twice to test repeatability of results.

Results of the 90 degree and the 45 degree spray angles were significantly different. Results of 90 degree showed the suppression was achieved above a critical line. Operating in a regime below the critical line will not yield a complete suppression condition (i.e., extinguishment) and any operating regime above the line will guarantee extinguishment for the case without the calorimeter. To guarantee extinguishment for the case with the calorimeter, a certain marginal tolerance needs to be considered. Results of 45 degree spray angle suppression tests were less repeatable. Fire extinguishment was consistently achieved when the operating pressure was greater than 190 psi but only for the case without the calorimeter. Since test data for the 45 degree spray angle configuration were not repeatable, this data is not recommended for model validation.

Data was obtained to conclude that the criterion for complete suppression depends on a combination factors which include: (1) nozzle diameter, (2) operating conditions, and (3) whether the calorimeter is present or not.

In additions to test data, nozzle spray droplet diameters and velocities were obtained for various nozzles used in these experiments. This data can be used to define water spray boundary conditions for model validation purposes.

Appendix A Gaseous Suppressants

The gaseous agent(s) that hold promise for fire suppression for military applications is based on the available data [1] and on the mechanism(s) used to suppress a fire. Gaseous suppressants fall into two main categories, those that suppress fires via dilution and by thermally removing heat, and those that suppress fires by dilution, thermally removing heat and by reacting chemically with radicals in the flame. The suppressants listed in Table A1 below are of both kinds and were developed for facilities. They were in various stages of commercialization as of March 2002 (Table A2).

Table A1 Gaseous Alternatives to Halon [2, 3]

Generic Name	Trade Name	Group	Chemical Composition
HFC-23	FE-13	HFC	CHF3
HFC-125	FE-25	HFC	CF3CHF2
HFC-227ea	FM-200	HFC	CF3CHFCF3
HFC-236fa	FE-36	HFC	CF3CH2CF3
HCFC Blend A	NAF S-III	HCFC+Blend	CHCLF2+CHCLFCF3+CHCL2CF3+C10H16
HCFC-124	FE-24	HCFC	CHCLFCF3
FC-2-1-8	CEA-308	PFC	CF3CF2CF3
FC-3-1-10	CEA-410	PFC	C4F10
FIC-1311	Triodide	FIC	CF3I
IG-01	Argotec	Inert Gas	A
IG-100	NN100	Inert Gas	N2
IG-55	Argonite	Inert Gas Blend	N2+A
IG-541	Inergen	Inert Gas Blend	N2+A+CO2

Table A2. Gaseous Total Flooding Agents-Progress Towards Commercialization

Generic name	Trade Name	Step 1 EPA SNAP List	Step 2 NFPA Standard	Step 3 Component Listing	Step 4 Listing in A System
HFC-23	FE-13	X	X	X	X
HFC-125	FE-25	X	X		
HFC-227ea	FM-200	X	X	X	X
HFC-236fa	FE-36	X	X		
HCFC Blend A	NAF S-III	X	X		
HCFC-124	FE-24	X	X	X	X
FC-2-1-8	CEA-308	X	X		
FC-3-1-10	CEA-410	X	X		X
FIC-1311	Triodide	X	X		
IG-01	Argotec	X	X	X	X
IG-100	NN100	X	X		
IG-55	Argonite	X	X		
IG-541	Inergen	X	X	X	X

For a halon alternative to reach commercial acceptance in the US, there are at least four steps in the process and until all four are achieved, the agent will see little or no success. These steps, in chronological sequence are:

1. Inclusion in the US EPA's SNAP[1] list as an acceptable alternative where the focus is primarily on the health and environmental effects of the agent.
2. Inclusion of the agent in a technical standard of the National Fire Protection Association which is intended to provide guidelines to the users concerning the design, installation, operation, testing and maintenance of systems or extinguishers employing the agent.
3. Component listing or approval of the agent itself by a nationally recognized testing laboratory such as Underwriters laboratories or Factory Mutual.
4. Listing or approval by a nationally recognized testing laboratory of a fire extinguishing system or hand portable extinguisher incorporating the agent.

To determine the best agent for fighting fires with flammable liquids, oils, greases, tars, oil-base paints, lacquers and flammable gases (Class B fires), effectiveness may be compared to those agents developed for portable fire extinguishers by Underwriters Laboratories (UL) and industry. The ultimate rating of an extinguisher or the prescribed use of an extinguisher or agent is based on its fire-extinguishing potential as determined by fire tests and presupposes installation and use in accordance with the "Standard for Portable Fire Extinguishers", NFPA 10.

Class B fires are performed on square metal pans as summarized in Table A3 (4). The classification and rating format contains a number preceding the classification for the type fire for which it is rated. The number represents a rating based on the size of the test fires with larger numbers indicating greater effectiveness. The numerical value of the B rating is 40% of the area of the test pan. This relationship was established several years ago when it was determined through fire testing with novices that they could achieve extinguishment proficiency equal to 40% of that of a professional fire fighter doing UL testing. In other words, a professional fire fighter could extinguish a fire 100 square feet in area with a given extinguisher, a novice using the same extinguisher could be expected to extinguish a fire no more than 40 square feet in area. It would be expected therefore that in the absence of a "smart" system in a facility, ratings would be less than that given for novice fire fighters. The following table gives the rating and class of an extinguisher, whether or not it was an indoor or outdoor test, the pan size the minimum effective discharge time and the type of fuel tested.

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[1] Under section 612 of the Clean Air Act, EPA established the Significant New Alternatives Policy (SNAP) program. SNAP's mandate is to identify alternatives to ozone-depleting substances and to publish lists of acceptable and unacceptable substitutes. Several rules and notices have expanded these lists, and they are available for online reading or for downloading (http://www.epa.gov/ozone). In addition, fact sheets cover more fully the eight industrial sectors included within SNAP. Finally, information about enforcement actions is available. "United States Environmental Protection Agency SNAP Program," Title 49, Code of Federal Regulations, Part 111.59, Sub-Chapter J, Federal Register, Volume 59, Page 13044.

Table A3. Flammable Liquid Arrangement for Class B Fire Test

Rating-Class	Indoor or Outdoor Test	Pan Size (Square Feet)	Minimum Effective Discharge Time (seconds)	Commercial Grade Heptane Used (gallons)
1-B	Indoor	2.5	8	3.3
2-B	Indoor	5.0	8	6.3
5-B	Indoor	12.5	8	15.5
10-B	Indoor	25.0	8	31.0
20-B	Indoor	50.0	8	65.0
30-B	Outdoor	75.0	11	95.0
40-B	Outdoor	100.0	13	125.0
60-B	Outdoor	150.0	17	190.0
80-B	Outdoor	200.0	20	250.0
120-B	Outdoor	300.0	26	375.0
160-B	Outdoor	400.0	31	500.0
240-B	Outdoor	600.0	40	750.0
320-B	Outdoor	800.0	48	1000.0
480-B	Outdoor	1200.0	63	1500.0
640-B	Outdoor	1600.0	75	2000.0

For portable fire extinguishers, the list of gaseous agents that replaces halon is much shorter. There are currently 7 that are on the SNAP list as of March 2002. Table A4 is a listing of the available alternatives.

Table A4. Gaseous Alternatives to Halon for Portable Extinguishers

Generic Name	Trade Name	Group	Chemical Composition
HCFC Blend B	Halotron I	HCFC+Blend	Blend of $CHCl_2CF_3$, CF_4 and Argon
HCFC Blend E	NAF P-IV	HCFC+Blend	Blend of $CHCl_2CF_3$, CF_3CHF_2 and $C_{10}H_{16}$
HCFC-124	FE-24	HCFC	$CHClFCF_3$
HFC-236fa	FE-36	HFC	$CF_3CH_2CF_3$
HFC-227ea	FM-200	HFC	CF_3CHFCF_3

The status of the gaseous agents for portable fire extinguishers showing which steps have been achieved towards commercialization list is shown in Table A5.

Table A5. Gaseous Streaming Agents – Progress Toward Commercialization

Generic Name	Trade Name	Step1 EPA SNAP List	Step 2 NFPA Standard	Step 3 Component Listing	Step 4 Listing in a Portable Extinguisher
HCFC Blend B	Halotron I	X	X	X	X
HCFC Blend E	NAF P-IV	X			
HCFC-124	FE-24	X			
HFC-236fa	FE-36	X	X	X	X
HFC-227ea	FM-200	X	X	X	X

When comparing the fire ratings of halon 1211 extinguishers to those of similar sizes using HFC-236fa and HCFC Blend B, the ratings illustrated in Table 6 indicate that the agents are in the same range of effectiveness. That is, a halon 1211 unit with 9 pounds of agent has the same rating as an HFC-236fa unit with 9.5 pounds of agent which has the same rating as an HCFC Blend B extinguisher with 11 pounds of agent.

Appendix B Nozzle Droplet Data

The following table shows the nozzles tested by Spraying Systems, Co. All nozzles were full solid cone. This type of nozzle gives a uniform, round, full spray pattern with medium-to-large droplet size.

Nozzle Model No.	Nozzle Diameter (in)
30200	0.344”
30250	0.375”
30300	0.406”
30350	0.438”
30400	0.469”

Tables B1 through B5 show data collected with the Phase Doppler Particle Analyzer (PDPA). The x-position corresponds to the location where the measurement sample was taken from along the diameter of the nozzle spray; zero is the center of the nozzle spray. PDPA obtain sample distribution over a differential volume. D_{Vn}, is the value where *100n* percent of the total volume sampled is made up of droplets with a diameter greater and less than D. For example, in Run 1 of Table B1, 50% of the total volume sampled had droplets with diameters greater and less than 778.1 µm (i.e., 778.11 µm is the median droplet volume diameter). V_{AVG} is the mean velocity of droplets sampled and V_U is the uncertainty in V_{AVG}.

Table B1. Nozzle 30200 Droplet Size and Velocity Data

Run #	x-Position (mm)	Pressure (psi)	$D_{V0.1}$	$D_{V0.5}$ (µm)	$D_{V0.9}$	V_{AVG}	V_U (m/s)
1	0	40	237.8	778.1	1656.7	9.9	2.9
2	-101.6		322.4	735.8	1245.3	9.7	3.1
3	-203.2		279.7	705.6	1272.8	7.4	3.2
4	0	60	165.5	729.4	1877.5	12.1	3.2
5	-101.6		176.8	729.9	1802.3	11.4	3.4
6	-203.2		187.9	675.6	1527.7	7.7	3.1
7	0	80	131.7	575.3	1472.9	14.3	3.4
8	-101.6		182.2	580.3	1214.5	13.0	3.6
9	-203.2		259.6	497.8	754.0	8.1	3.1
10	0	100	109.3	519.7	1404.3	16.5	3.5
11	-101.6		194.2	468.5	821.2	14.9	3.6
12	-203.2		86.6	470.7	1385.7	8.3	3.0
13	0	170	44.4	488.4	2252.6	22.0	3.8
14	-101.6		161.4	391.5	688.6	17.7	3.7
15	-203.2		202.6	331.8	454.4	8.2	2.6
16	0	200	136.5	426.6	882.0	24.5	4.0
17	-101.6		174.2	357.1	564.4	18.3	4.2
18	-203.2		197.5	303.5	399.1	8.3	2.6

Table B2. Nozzle 30250 Droplet Size and Velocity Data

Run #	x-Position (mm)	Pressure (psi)	$D_{V0.1}$	$D_{V0.5}$ (μm)	$D_{V0.9}$	V_{AVG}	V_U (m/s)
1	0	20	403.8	836.5	1330.8	7.9	2.0
2	-101.6		340.4	1030.3	2087.4	7.1	2.0
3	-203.2		513.7	1008.0	1549.1	5.7	2.3
4	0	40	265.7	730.4	1391.7	10.6	2.5
5	-101.6		336.6	836.0	1493.2	9.7	2.8
6	-203.2		350.3	850.4	1496.7	7.3	3.0
7	0	60	155.9	623.2	1508.0	13.8	2.8
8	-101.6		195.3	678.5	1501.0	11.7	3.2
9	-203.2		243.2	683.1	1319.6	8.4	3.1
10	0	80	202.6	517.2	940.2	15.8	3.1
11	-101.6		226.7	521.9	888.1	13.1	3.5
12	-203.2		135.3	609.6	1592.0	8.9	3.2
13	0	100	148.2	538.1	1224.3	17.9	3.1
14	-101.6		168.9	519.4	1063.1	14.9	3.6
15	-203.2		217.7	469.5	766.4	9.0	3.2
16	0	170	155.2	500.9	1057.4	25.9	3.8
17	-101.6		196.7	414.1	665.6	20.1	4.0
18	-203.2		201.3	338.1	470.6	9.5	3.0

Table B3. Nozzle 30300 Droplet Size and Velocity Data

Run #	x-Position (mm)	Pressure (psi)	$D_{V0.1}$	$D_{V0.5}$ (μm)	$D_{V0.9}$	V_{AVG}	V_U (m/s)
1	0.0	20	450.7	954.1	1539.1	8.5	1.8
2	-101.6		509.5	1006.9	1554.4	7.9	2.1
3	-203.2		549.1	1052.0	1592.4	6.4	2.2
4	0.0	30	350.0	770.5	1274.3	10.4	2.0
5	-101.6		417.9	894.4	1452.8	9.9	2.3
6	-203.2		461.4	897.6	1372.0	7.4	2.7
7	0.0	40	315.3	724.4	1231.2	12.2	2.1
8	-101.6		294.5	851.4	1675.2	11.6	2.5
9	-203.2		369.7	777.1	1247.7	8.3	2.8
10	0.0	80	249.4	695.2	1336.5	18.0	2.7
11	-101.6		245.7	643.9	1190.1	16.8	3.0
12	-203.2		201.9	590.2	1169.5	10.4	3.3
13	0.0	100	248.6	624.4	1123.2	20.3	2.9
14	-101.6		137.7	606.2	1559.5	19.0	3.0
15	-203.2		212.7	481.0	809.2	11.3	3.5
16	0.0	111	214.2	661.6	1357.7	21.9	3.0
17	-101.6		235.6	532.8	896.5	20.4	3.0
18	-203.2		165.2	516.0	1066.7	11.5	3.5
19	0.0	122	234.3	552.5	954.7	22.9	3.1
20	-101.6		213.6	543.4	985.5	21.5	3.1
21	-203.2		212.2	414.3	634.6	11.5	3.6

Table B4. Nozzle 30350 Droplet Size and Velocity Data

Run #	x-Position (mm)	Pressure (psi)	$D_{V0.1}$	$D_{V0.5}$ (μm)	$D_{V0.9}$	V_{AVG}	V_U (m/s)
1	0.0	15	593.0	1155.1	1767.1	7.6	1.9
2	-101.6		692.9	1231.5	1776.9	6.2	2.3
3	0.0	30	436.5	1072.7	1903.0	10.8	2.6
4	-101.6		427.2	1023.0	1785.2	7.8	3.2
5	-152.4		461.3	869.1	1301.7	6.5	2.9
6	0.0	50	318.0	897.0	1737.6	13.7	3.0
7	-101.6		303.2	868.3	1698.1	9.4	3.7
8	-152.4		317.7	783.9	1394.4	7.3	3.3
9	0.0	60	290.5	884.5	1798.7	15.3	3.2
10	-101.6		251.3	925.8	2126.2	10.3	3.9
11	-152.4		307.7	648.6	1043.6	7.9	3.3
12	0.0	82	207.1	754.8	1721.5	18.1	3.4
13	-101.6		149.2	652.0	1669.8	11.3	4.1
14	-152.4		231.6	567.1	1003.8	8.3	3.4
15	0.0	92	195.4	709.3	1613.7	19.4	3.4
16	-101.6		105.7	634.3	1988.6	12.3	4.3
17	-152.4		234.4	485.4	772.3	8.6	3.5

Table B5. Nozzle 30400 Droplet Size and Velocity Data

Run #	x-Position (mm)	Pressure (psi)	$D_{V0.1}$	$D_{V0.5}$ (μm)	$D_{V0.9}$	V_{AVG}	V_U (m/s)
1	0.0	10	523.3	1019.0	1558.7	5.7	1.5
2	101.8		557.5	1060.9	1599.1	5.3	1.8
3	203.6		667.9	1147.6	1620.6	4.8	1.9
4	0.0	15	459.0	957.2	1529.3	6.7	1.6
5	101.8		485.7	980.1	1533.5	6.1	1.9
6	203.6		618.4	1104.2	1598.0	5.5	2.2
7	0.0	20	419.2	901.3	1468.3	7.9	1.8
8	101.8		430.7	875.3	1375.8	7.3	2.1
9	203.6		550.9	1041.5	1563.3	6.1	2.5
10	0.0	30	331.8	763.8	1299.6	9.8	2.1
11	101.8		333.1	760.5	1287.3	8.9	2.5
12	203.6		460.9	930.6	1456.5	7.3	3.0
13	0.0	40	284.1	705.9	1261.0	11.4	2.3
14	101.8		306.5	702.1	1190.8	10.1	2.9
15	203.6		373.8	793.2	1281.5	8.3	3.3
16	0.0	62	232.5	968.2	2404.0	14.2	2.8
17	-101.8		162.4	664.3	1631.0	12.7	3.5
18	-203.6		222.2	746.6	1616.9	9.1	3.9
19	0.0	74	226.6	567.6	1019.4	15.9	3.0
20	101.8		229.1	538.2	927.8	15.0	3.3
21	203.6		199.6	646.3	1367.0	11.3	3.9

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