SUPPRESSION OF GAS WELL BLOWOUT FIRES USING WATER SPRAYS; LARGE AND SMALL SCALE STUDIES

by

Dwight Pfenning
Energy Analysts, Inc.
Norman, OK

and

David Evans
Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
U.S. Department of Commerce
Gaithersburg, MD 20899

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Dwight Pfenning
Energy Analysts, Inc.
Norman, Oklahoma

David Evans
National Bureau of Standards
Washington, DC

Abstract

Large scale simulation tests were conducted to demonstrate the effectiveness of water spray systems to control and extinguish gas well blowout fires. Selected results from small scale experiments performed in this research program are given primarily to help explain the development of the water spray extinguishment method, but also to examine scaling of important phenomena. Two techniques of water spray injection, internal and external to the initial gas jet, were tested at large scale on fires with heat release rates from 144 megawatts (138 SCFS methane flow) to 222 megawatts (212 SCFS methane flow). Using external water injection from four nozzles surrounding the gas jet, fires of almost 200 megawatt size could be extinguished with a mass flow ratio (water/gas) of 2.17 (129 GPM water flow) and continued to burn at a ratio of 1.56 (86 GPM water flow). This technique of water injection could be the basis of a practical blowout fire suppression system.

Key words: blowout fires, extinguishment, water spray.

1. INTRODUCTION

The blowout of oil and gas wells during drilling, production, and work-over presents a serious hazard to personnel, the environment, and equipment. The only practical method to control a well fire subsequent to a blowout is to shut in the hydrocarbon flow at the well. Well blowout fires normally create large heat radiation hazard zones, both to personnel and equipment. Consequently, it is extremely hazardous for personnel to approach these fires in the fire control process. Also, the heat radiation load on well control equipment can be so severe that this equipment is damaged and control functions cannot be achieved with normal well head control procedures.

Little quantitative data are available that describe the size (height and diameter) of full scale well fires, the temperature profiles within the fire zone, and the heat radiation hazard zones adjacent to a fire [1]. Further, although some individuals have effectively used water to mitigate well fire hazards, the quantitative effect of water sprayed into the fire zone is not known. To design effective oil and gas well blowout fire control systems, both the hazards associated with the fire and the efficiency of water to control fire hazards must be quantitatively understood [2].

Laboratory scale studies have been conducted at the Center for Fire Research (CFR) of the National Bureau of Standards (NBS) to quantify the effects of water sprays on jet flames that are characteristic of gas well blowout fire accidents. This work was part of a large research program of technology assessment for offshore minerals operations supported by the Minerals Management Service (MMS) of the Department of Interior [3]. It was shown in these laboratory studies of fires with heat release rates from 0.1 to 10 megawatts that it was feasible to reduce radiation from jet flames and extinguish the fire using relatively small quantities of water [4]. The efficiencies of many different water spray system geometries in terms of ability to extinguish fires have been studied. The most efficient spray geometries were tested at large scale for CFR by Energy Analysts, Inc. to demonstrate scaling of laboratory results for reduction in flame radiation, reduction in gas temperatures, and extinguishment efficiency. These large scale tests consisted of a series of seven tests to quantify the burning characteristics of high velocity methane gas discharges that simulate accidental gas well blowouts.

2. TEST FACILITIES

This study involved studies at two research laboratories. One is the Center for Fire Research at the National Bureau of Standards in Gaithersburg, Maryland. The other is Energy Analysts, Inc. in Norman, Oklahoma.

2.1 CFR Laboratory Test Facilities

Two scales of laboratory experiments were conducted by CFR to examine the phenomena of reduction in flame radiation and fire extinguishment. Bench scale experiments with fire heat release rates of up to 0.1 megawatts (1 m flame height) were performed under hoods in general laboratory space. Larger experiments up to 10 megawatts heat release rate (5 m flame height) were performed in the CFR Blowout Fire Suppression Facility a concrete pit test facility operated by NBS. This pit facility provided a compartmented testing site with the floor approximately 4 m below ground level. Extinguishment tests of simulated blowouts were performed under a large ceiling vent at ground level. This below ground arrangement for the gas jet release provides for shielding of the flame base from the wind. Measurements of axial flame and plume temperatures and radiative heat flux from the flame were routinely performed. Methane gas flows were burned in a jet after being forced through orifice plates mounted at the exit of a 4 in diameter piping system. Water spray nozzles were mounted both inside the supply gas pipe to provide internal water injection and surrounding the supply pipe to provide various external spray geometries, see figure 1. Additional information on the small scale test facility can be found in reference 4.

2.2 Energy Analysts' Large Scale Test Facility

Energy Analysts' test site was located fifteen miles south of Oklahoma City. The test site was an open area on the flood plain of a river, and the nearest inhabitants were three-fourths of a mile from the site. The layout of the test facilities is presented in Figure 2.

High pressure 17,000 kPa (2500 psig) over-the-road tank trucks were used as supply gas which was 96.35% methane by volume for testing. The remaining fraction contained other higher molecular weight alkanes, nitrogen, and carbon dioxide. Gas flow rates from the ten cylinder truck manifold were controlled with a pressure regulator on the unloading platform. Flow rates were calculated from differential pressure measurement across orifice plates in the 0.15 m (6 in) diameter gas supply pipe.

Water for the tests was supplied from a 14,000 liter (3750 gallon) tank, and pressurized using a diesel engine powered pump capable of delivering up to 63 LPS (1000 gpm) at 690 kPa (100 psig). Water flow was controlled manually and measured by pressure differential across an orifice plate installed in the 0.15 m (6 in) diameter water supply pipe.

Two types of spray headers were used for the tests. The first type header discharged water from a 15° solid spray cone nozzle inside the gas discharge (see figure 3). The nozzle was centered in the gas pipe approximately 0.05 m (2 in) below the bottom of the restriction orifice plate at the gas discharge. The alternate spray header consisted of four 15° solid spray cone nozzles placed around the gas discharge (see figures 4 and 5). Distance from the center of the gas discharge to the center of each water nozzle was 0.23 m (9 in). All nozzles were fitted on 0.05 m (2 in) threaded pipe. The water piping was anchored at a concrete pad supporting both the gas and water outlet piping.

An array of 20 (type K) thermocouples with 0.5 mm bead size was used to measure the temperature profile of the flame, both axially and radially. Two 24.4 m (80 ft) towers were erected at the site (see figure 6) as supports for the array. The towers were 15.2 m (50 ft) apart, with the gas outlet pipe located halfway between the towers. A system of pulleys and take-up reels was attached to the towers enabling the three stainless steel cables used to raise and position the array above the gas outlet. The array was laid out as an inverted triangle, with the apex of the triangle fastened to the piping just below the gas outlet. Thermocouple positions are shown in figure 7.

Five Gardon type heat flux transducers with sapphire windows were used to measure the radiant heat flux. These radiometers were calibrated with windows in place using black body sources over the range of use. They were placed at the locations indicated in figure 7. Radiometer R1 had a narrow angle (7° viewing cone) and was used to obtain a value for the effective surface flux of the flame. All other radiometers had 150° viewing cones. With the exception of radiometer R3, the radiometers were focused in the plane formed by the towers. Radiometers R1, R3, and R4 were focused on the intersection of the middle vertical and middle horizontal cables, (see figure 7). Radiometer R3 was placed just out of the tower plane such that the 150° viewing angle just missed the tower. Radiometer R2 was placed at the top of one tower.

In addition to the instrumentation for measuring water and gas flows, temperature, and flame radiation, a set of meteorological instruments were used to record the wind speed, wind direction, wet bulb temperature, and dry bulb temperature. All of the sensors had a voltage or millivolt output that was scanned once per second by the data acquisition system. Color video, 16 mm color film, and 35 mm side records were made of all large scale tests.

2.3 Testing Program

In both laboratory and large scale testing, measurements were made on stable vertical flame jets established above the gas outlet. Temperature and radiations measurements were made over a 15 to 30 second period after ignition. Water was then applied. If the flame was not extinguished and a new stable flame condition was achieved measurements were taken over an additional 15 to 30 second period. Generally if the flame was not extinguished by the water flow, radiation was reduced and the lift-off height increased.

Many laboratory studies were conducted to try and quantify the interaction of water spray with the jet flame. Only seven large scale tests were performed with fires from 144 to 222 megawatts heat release rate, see table 1. Of the seven tests performed, tests 4, 5, and 6 provided the best measurements of temperature and radiation, because the low local wind speeds of approximately 0.45 m/s (1 mph) were insufficient to tilt the flame away from thermocouples and radiometers placed to measure conditions directly over the gas outlet in the plane of the two support towers. The undistorted vertical flame-jets in these large scale tests, were geometrically similar to those studied at small scale and provide the best basis for comparing the effectiveness of water sprays to extinguish the fires.

3. TEST RESULTS AND DISCUSSION

3.1 Extinguishment Efficiency

Small scale testing in the CFR Blowout Fire Suppression Facility, figure 1, was used to determine the efficiency of fire extinguishment for many different water spray geometries. The measure of effectiveness was the ratio of mass flow rate of water to mass flow rate of fuel being burned ($\dot{m}_w/\dot{m}_g$) at extinguishment. At the beginning of these gas-well suppression studies it was thought that an effective blowout fire suppression system could be built and supplied with water using pumping capabilities available on the offshore platforms, if the ratio $\dot{m}_w/\dot{m}_g$ for extinguishment was below 10.

Several spray geometries that directed spray at the base of the flame were found to be capable of extinguishing the fire, but relatively inefficient with $\dot{m}_w/\dot{m}_g$ ratios of 6.4 and 9.5 for extinguishment, see figure 8. A nozzle system design that abandoned any intentional pointing of the spray at a particular part of the flame, by spraying water vertically parallel to the flame axis, was found to be very efficient. In tests, at small scale, a two nozzle water spray system was able to extinguish fires at an effectiveness ratio $\dot{m}_w/\dot{m}_g$ = 4.2, with the discharge level at the same elevation as the gas outlet, 0.3 m below the base of the lifted flame, see figure 8. The effectiveness of this system was only slightly diminished by increasing the distance between the bottom of the flame and the water discharge by a factor of three. In this case, the ratio $\dot{m}_w/\dot{m}_g$ at extinguishment increased about 26% to 5.3, see figure 8.

In small scale testing the system of nozzles that sprayed water vertically to surround the flame was both the most efficient external spray method tested and also the least sensitive to geometry changes between the flame base and water discharge points. A scaled-up version of this system was built for testing at large scale, figure 4, with the change that four nozzles would be used in large scale instead of the two used in small scale development work. This change was expected to make the system more effective because asymmetries of the two nozzle discharge would be reduced.

Large scale tests 4, 5, and 6 tested the effectiveness of this external spray system to extinguish fires with heat release rate from 186 to 205 megawatts (178 to 196 SCFS methane). In test 4, a ratio of $\dot{m}_w/\dot{m}_g$ = 4.26 was used to correspond to water flow rates shown to be effective at small scale. The flame was extinguished easily. In test 5, the water flow rate was decreased to 8.1 LPS (129 GPM) ($\dot{m}_w/\dot{m}_g$ = 2.17) the flame was extinguished in 5 seconds using only 40 liters (10 gallons) of water. Figure 9 shows photographs taken during this test. Decreasing the water flow further to 5.4 LPS (86 GPM) or $\dot{m}_w/\dot{m}_g$ = 1.56 for test 6 resulted in insuffient water flow to extinguish the fire. Figure 10 shows three photographs from test 6. This fire was interesting because two steady conditions were established; one, the natural burning of the methane, and two, the burning of the methane-water spray mixture. Measurements from this test will be discussed in the next sections.

The tests showed that the four nozzle spray system was more effective, $\dot{m}_w/\dot{m}_g = 2$ for extinguishment of large scale fires than the two nozzle systems $\dot{m}_w/\dot{m}_g = 4$ for extinguishment of small scale fires. Experiments are being planned to determine the ratio of water to gas mass flow ($\dot{m}_w/\dot{m}_g$) necessary to extinguish the gas fire with a four nozzle system at small scale.

3.2 Water Spray Cooling

Temperature measurements taken in and near the flame during test 6 both before and during water spray injection provide a means of quantifying temperature changes produced by the water spray. Temperature measurements were uncorrected for radiation effects. Figure 10 shows that the flame shape was changed dramatically by water injection. Figure 11 and 12 show temperature contour plots from individual data scans before and during water spray injection, respectively, from test 6. The addition of water spray increases the flame lift-off height and causes very steep temperature gradients 6 m to 9 m (20 ft to 30 ft) above the gas outlet. Figure 13 shows a plot of two axial temperature distributions; one averaged over 6 seconds of steady burning before water addition, and the other 15 seconds during the water application period. This plot shows clearly that even though the temperature distribution changes, peak temperatures in the flame only decrease about 100°C. Temperatures in the upper portion of the flame and plume are lowered by the heating and evaporation of water spray in the flame. Using data from laboratory scale tests with hydrogen jet-fires, McCaffrey [5] has correlated temperatures in the upper flame and plume both for the case of the flame alone and for the flame and water spray.

3.3 Reduction in Flame Radiation

In large-scale industrial flares water in the form of steam (or other diluents) can be pre-mixed with the effluent before it is burned to reduce smoke and soot formed [5]. Since soot is the dominant emitter of radiation from hydrocarbon flames, reduction in soot formation will produce a corresponding reduction in radiation. The reduction in visible radiation can be seen in the sequence of laboratory flames studied by McCaffrey [5] shown in figure 14. At the left, the burning propane jet produces a bright yellow flame. As finely atomized water spray is added to the fuel mixture, the flame changes at first to an orange color which becomes paler and more transparent as the water flow increases from left to right in the photographic sequence. Quantitative radiation measurements show that this water addition can reduce flame radiation to one-half of its original value without flame extinguishment [5].

Data from large scale test 6 can be used to determine the reduction in radiation produced by water spray injection. In the laboratory tests water was mixed with the gas flow by injecting water spray through the gas outlet (internal injection). In test 6, the water was injected external to the jet through four nozzles. Data from the four wide angle radiometers (R2, R3, R4, and R5 located as shown in figure 7) all show significant decreases in radiation after the water is applied, see figure 15. Data from R3 showed the greatest decrease in flame radiation but did not view the same plane as the others (see section 2.2). Both radiometers, R4 and R5, positioned near the ground below the flame measured a 30% decrease flame in radiation after water application. The actual change in total radiation from the flame is complicated to calculate because both the emissivity and shape of the flame change when water is applied and the water spray itself can absorb radiation.

Even without the addition of water the large methane jet-flames radiated a relative small amount of energy. Radiative flux to positions R4 and R5 was approximately 5 kW/m^2 before water injection in test 6. Approximating the flame as a symmetric, radiatively black source located on the axis of the flame 15 m above the gas outlet, the measured flux at R4 and R5 would require a total radiative loss of 14 MW or 7.5% of the total heat release rate.

3.4 Other Large Scale Tests

Tests 4, 5, and 6 provided the most useful and reliable measurements for the purpose of this study. Selected results from the other large scale tests are given in table 1. Tests 1 through 3 were tests in which water was injected through the gas outlet. Relatively high wind speed and some instrument problems reduced the usefulness of these tests. Test 7 provided good data for the flame alone. No water was applied during test 7. Further details of the experiments are provided in a report by Pfenning [6].

4. CONCLUSIONS

The mass flow ratio of water to fuel gas $(\dot{m}_w/\dot{m}_g)$ necessary to extinguish 200 megawatt methane jet-flames is between 1.6 and 2.2 using a system of four spray nozzles directing water vertically upward surrounding the flame. In cases where insufficient water is added to extinguish the flame, thermal radiation and plume temperatures are reduced. Laboratory tests have shown that radiation from propane jet-flames may be reduced by one-half before flame extinguishment. In one of the large scale tests with methane jet-fires, water spray reduced radiation to ground level by about 30%.

The large scale tests conducted in this study are an idealization of conditions during blowout fires. The heat release rate of these test fires is the same order of magnitude as expected blowout fires on offshore platforms. Testing in this program has shown that it is feasible to extinguish these fires and/or reduce radiation from the flame using water sprays.

5. ACKNOWEDGMENTS

The authors wish to thank Mr. John Gregory and Mr. Ed Tenneyson of the Minerals Management Services, DOI, for their continued interest in the progress of these studies. For his patience and supervision during the acquisition of gas for the large scale testing program, we would like to thank Mr. Ken Dickson, Process Engineer for the Phillips Kingfisher Gas Plant. It should also be recognized that these research test programs could only be completed with the help of many talented and experienced technical support personnel at both NBS and Energy Analysts.

6. REFERENCES

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Table 1. Gas and Water Flow Rates

Rates	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Injection location of water	internal	internal	internal	external	external	external	external
Gas flow rate (kg/sec)	2.69	4.2*	4.14	3.83	3.74	3.47	2.93
(SCFS)	138	220	212	196	192	178	150
Heat Release Rate (MW) (complete combustion)	144	230	222	205	201	186	157
Water flow rate (kg/sec)	1.6*	2.10	3.24	16.3	8.12	5.43	—
(GPM)	25.4	33.3	51.4	258	129	86.1	
Water flow rate/gas flow rate mass ratio	0.59	0.50	0.920	4.26	2.17	1.56	—
Average wind speed (m/s)	1.5 (σ=.2)	1.6 (σ=.3)	1.6 (σ=.2)	0.4 (σ=.07)	0.36 (σ=.11)	0.58 (σ=.08)	0.8 (σ=.02)
(mph)	3.4 (σ=.5)	3.5 (σ=.6)	3.5 (σ=.4)	0.9 (σ=.15)	0.8 (σ=.24)	1.3 (σ=.17)	1.8 (σ=.05)
Extinguished	yes†	no	no	yes	yes	no	no

* Approximation

† Flame tilted off axis by wind prior to water spray injection.

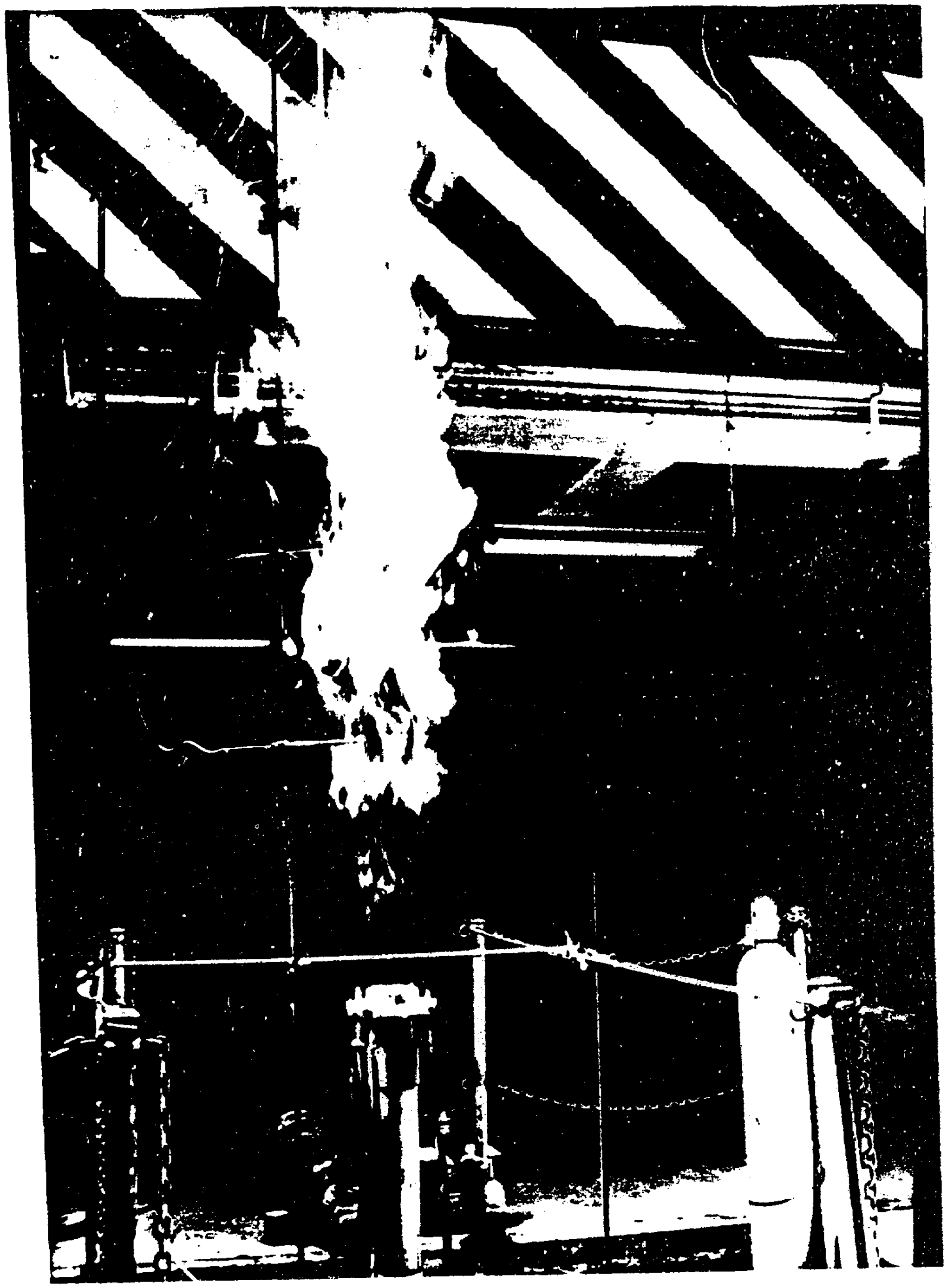


Figure 1   Center for Fire Research Blowout Fire Suppression Test Facility

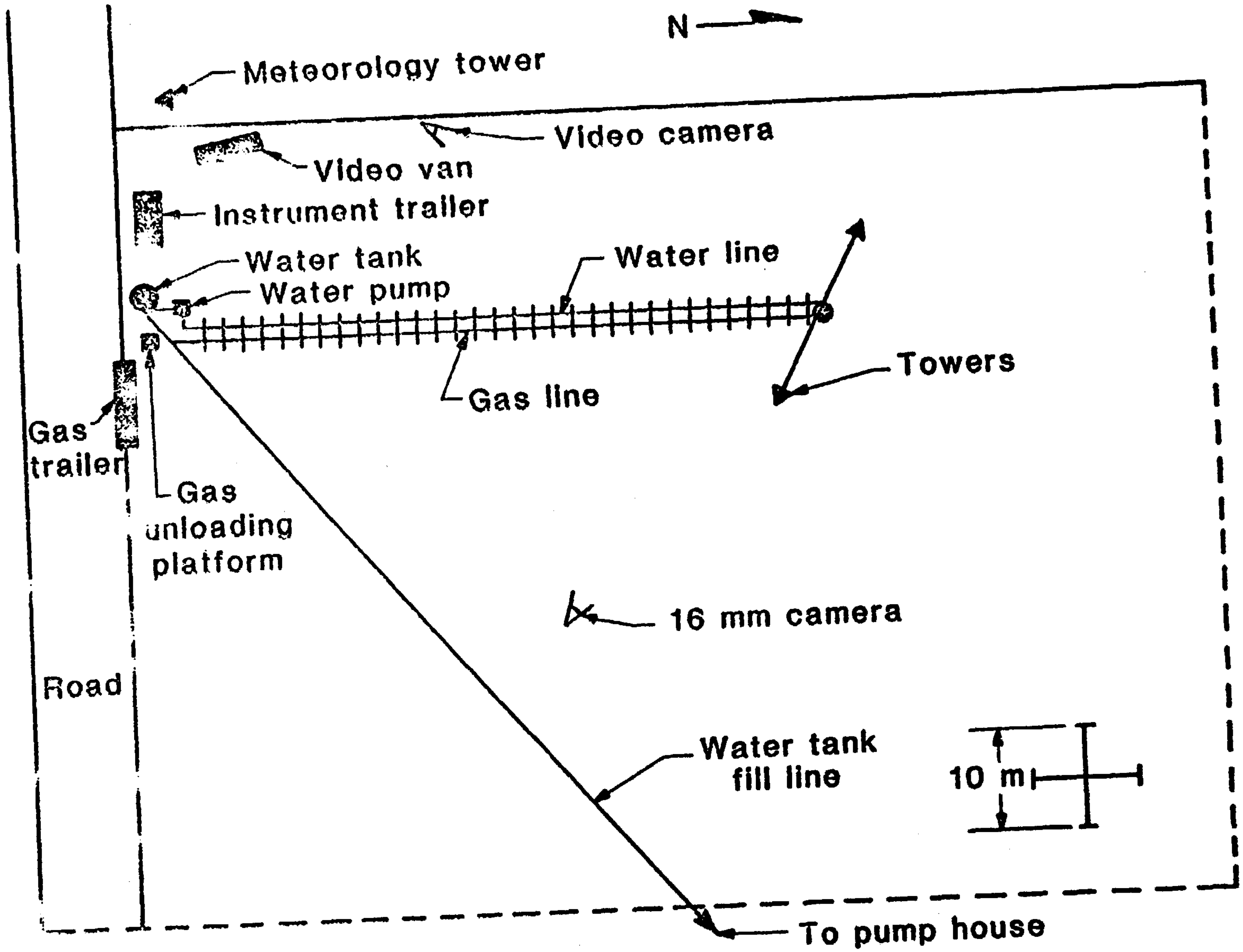
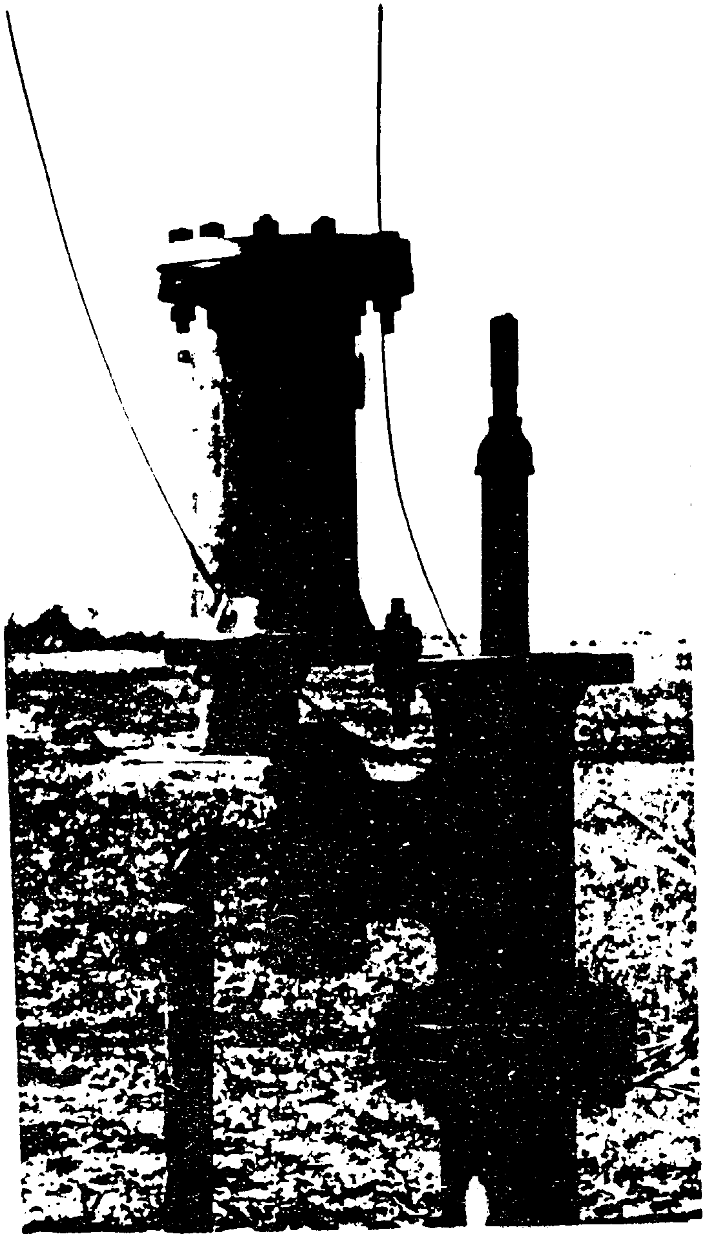
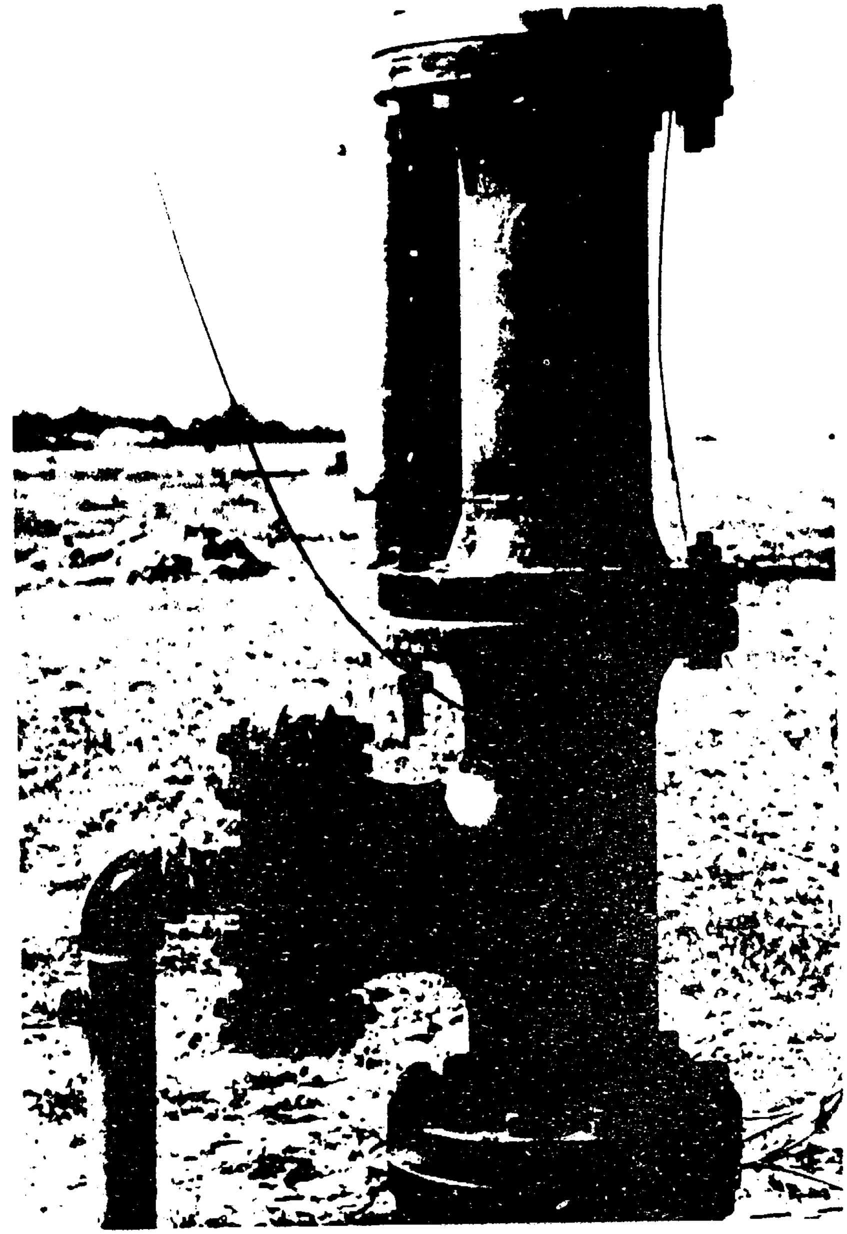


Figure 2 Plan View of Large Scale Test Site Layout



Nozzle Installed



Final Configuration

Figure 3 Internal Water Injection Configuration

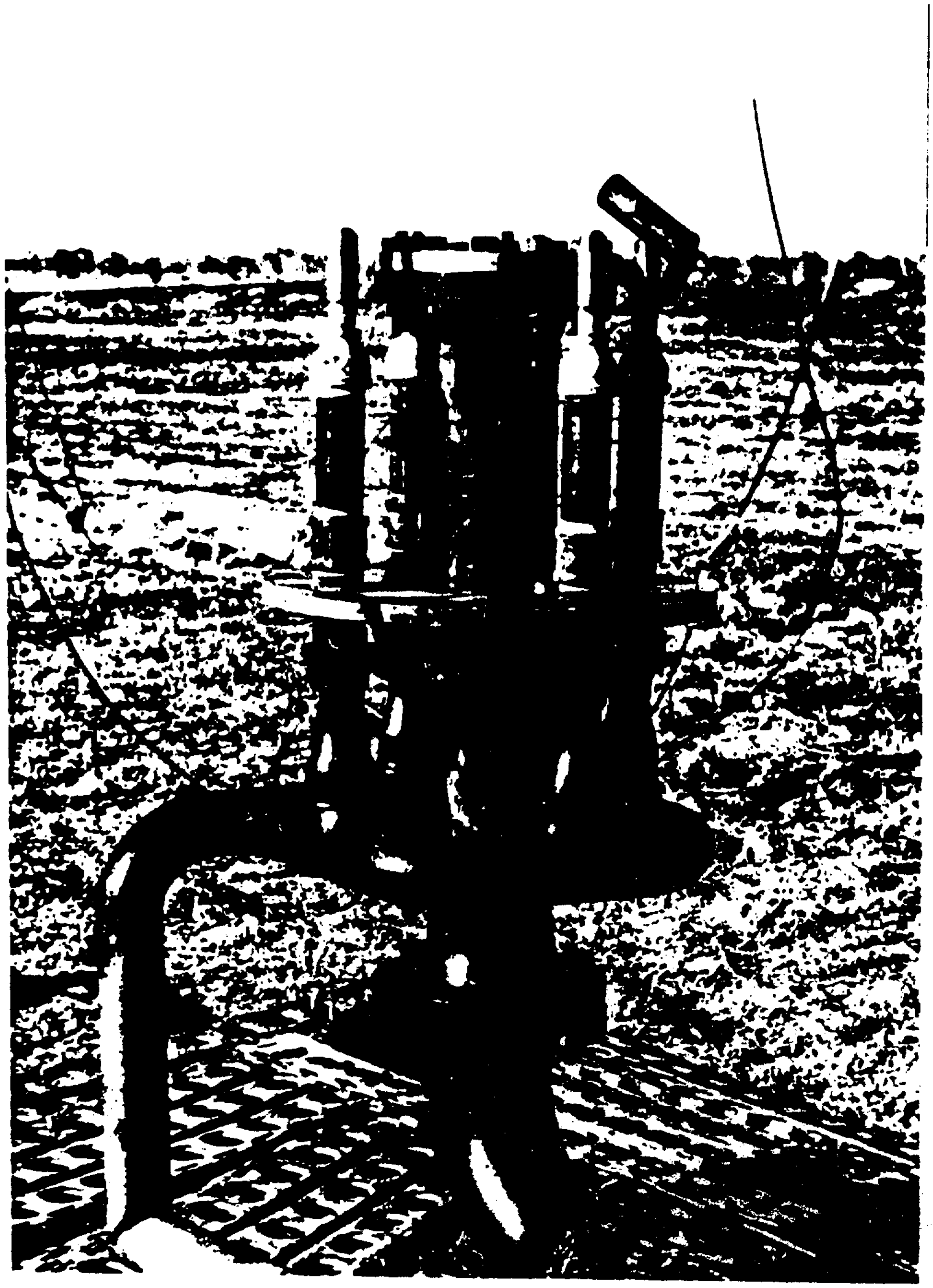
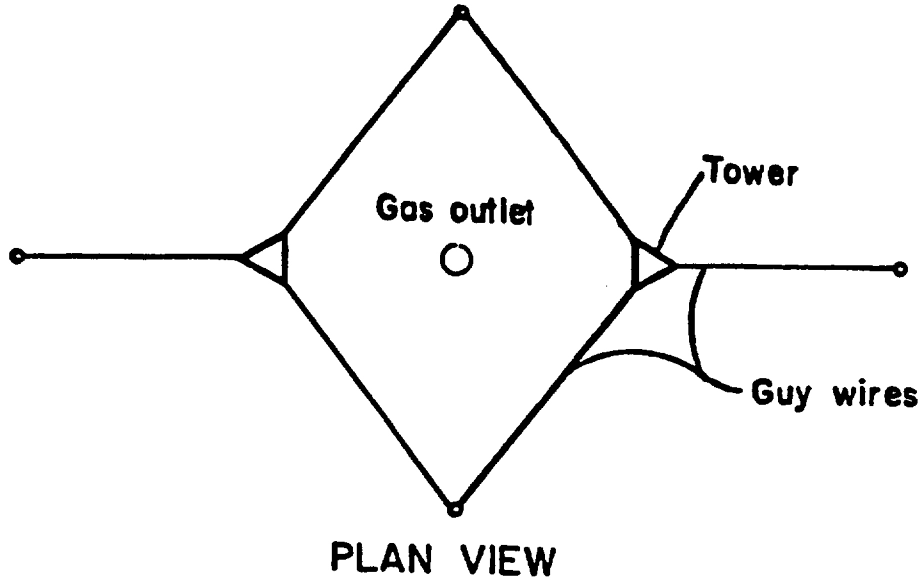


Figure 4   External Water Injection Configuration

Figure 5 External Water Injection Configuration with Restriction Orifice Gas Outlet in Place



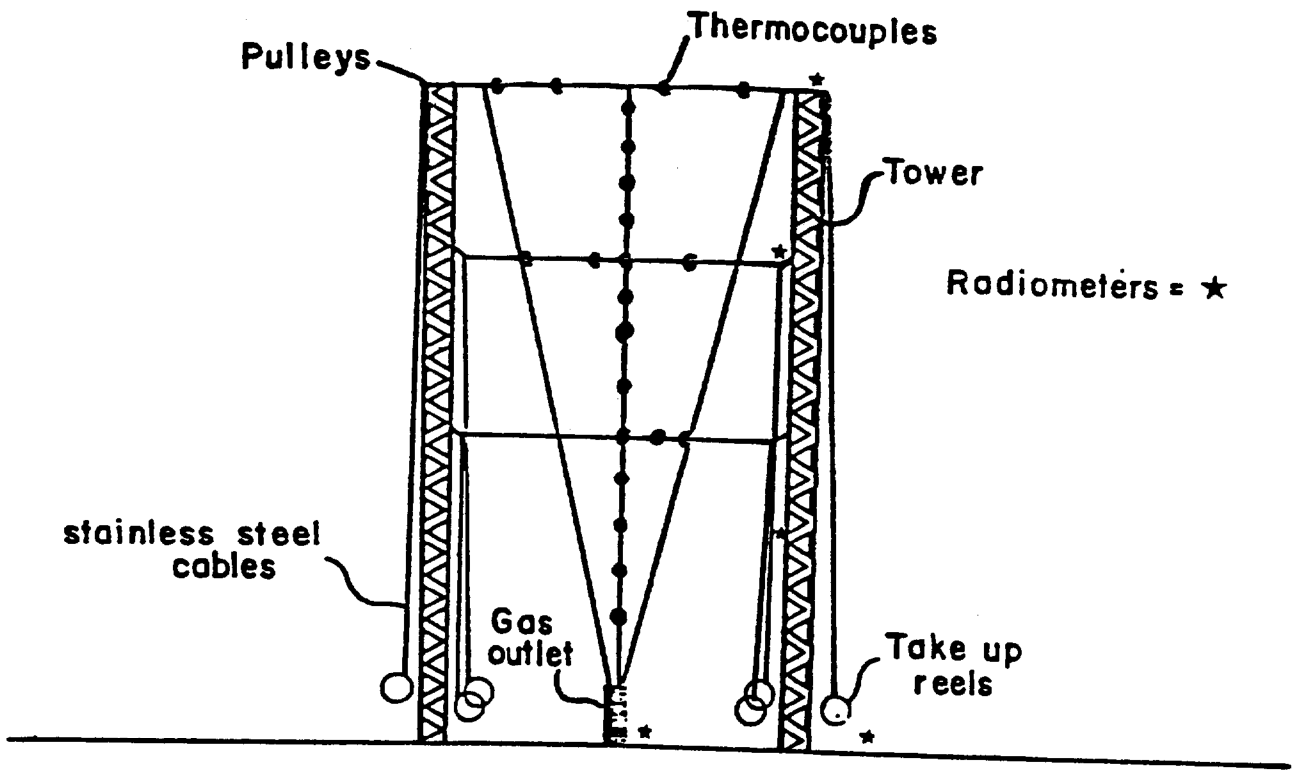


Figure 6 Plan and Elevation Views of Towers and Thermocouple Suspension System Used in Large Scale Tests

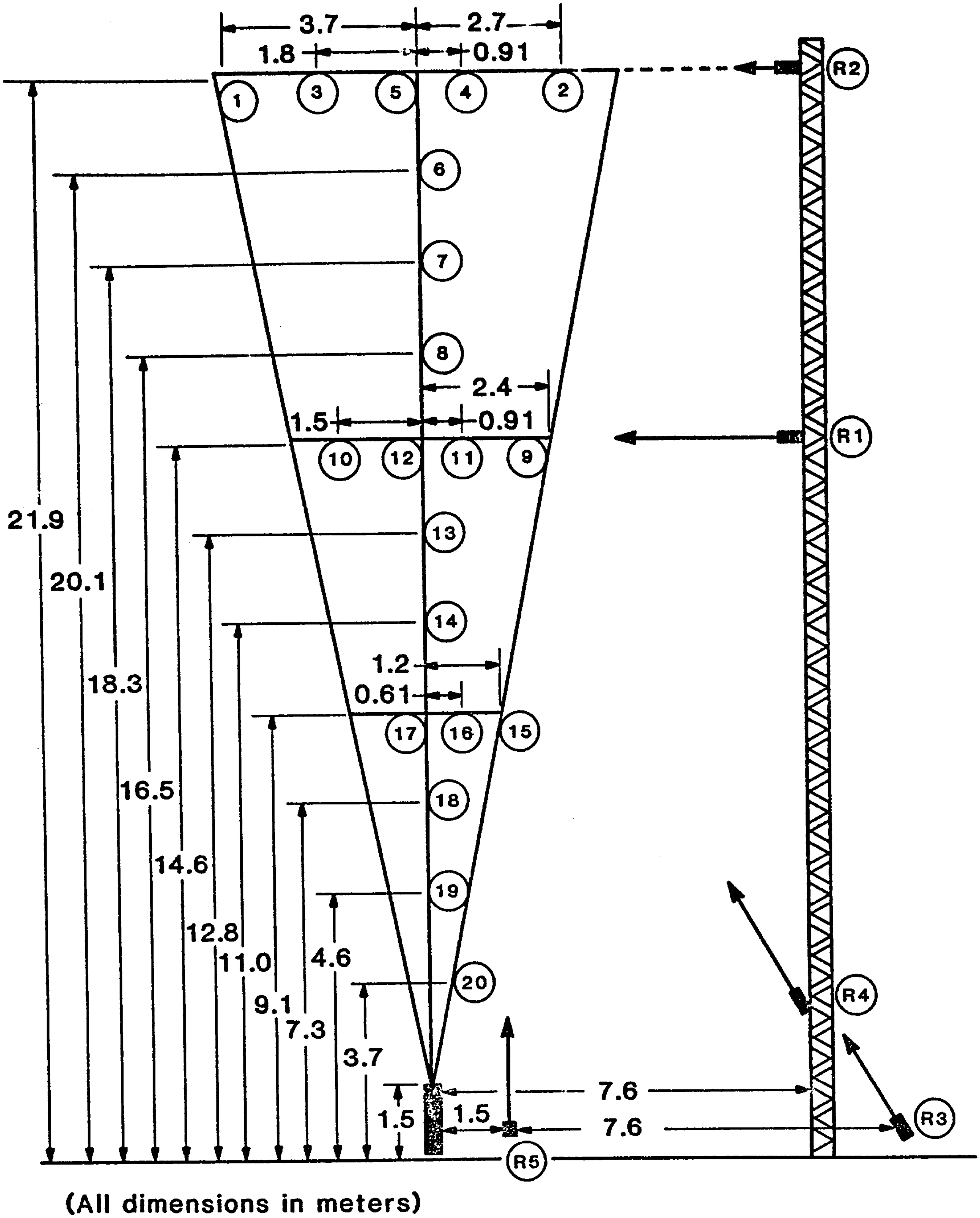


Figure 7 Diagram of Thermocouple and Radiomerter Positions

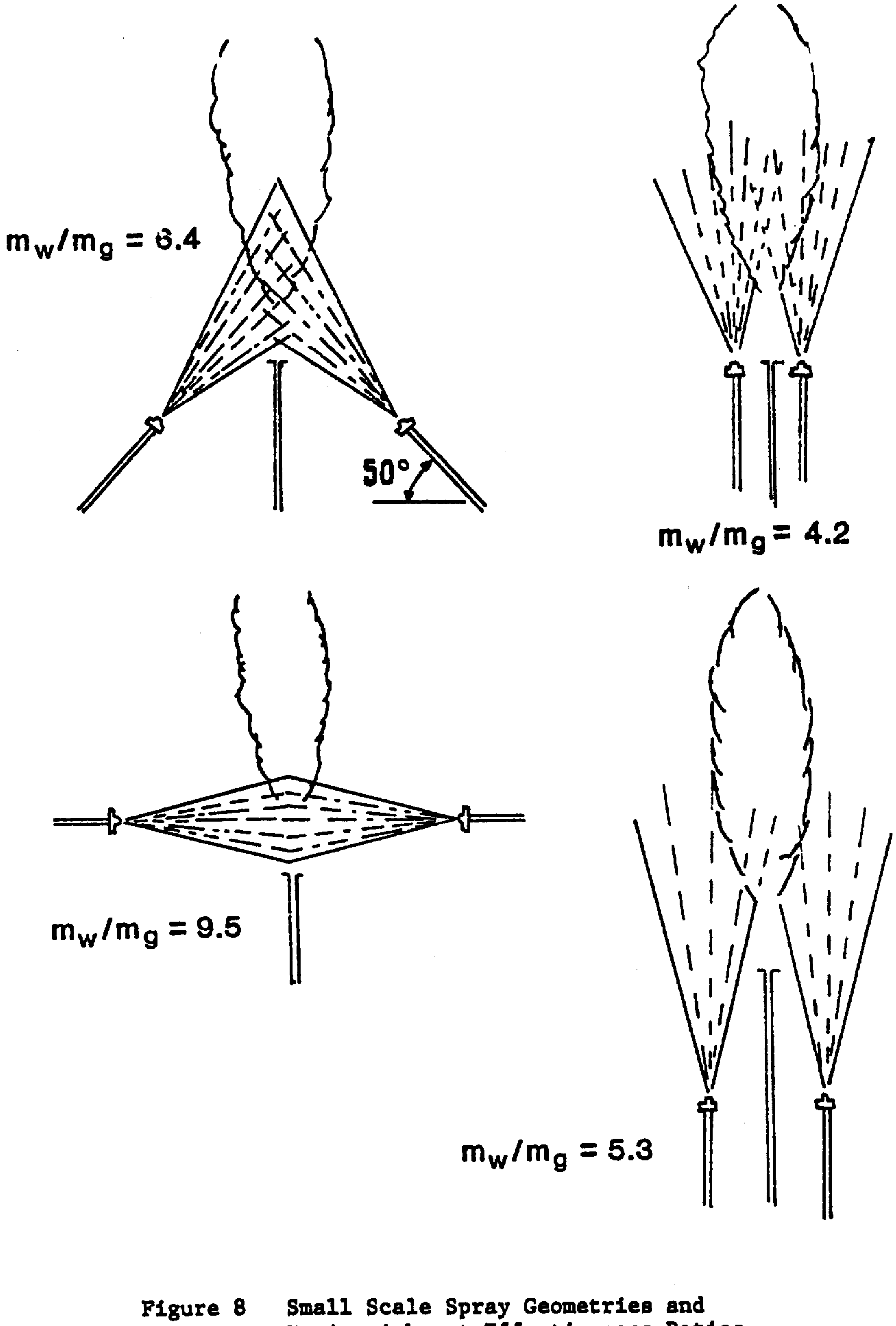
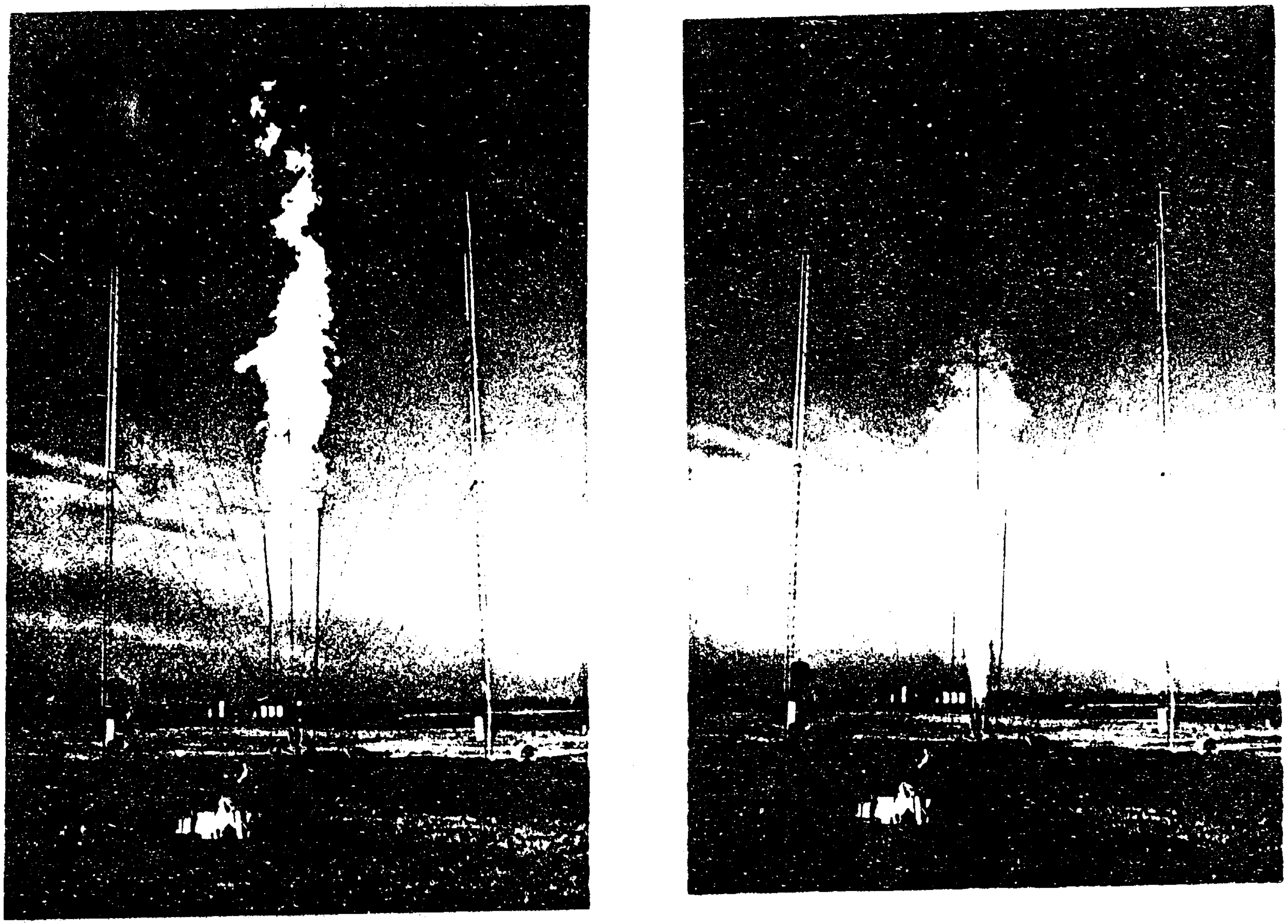


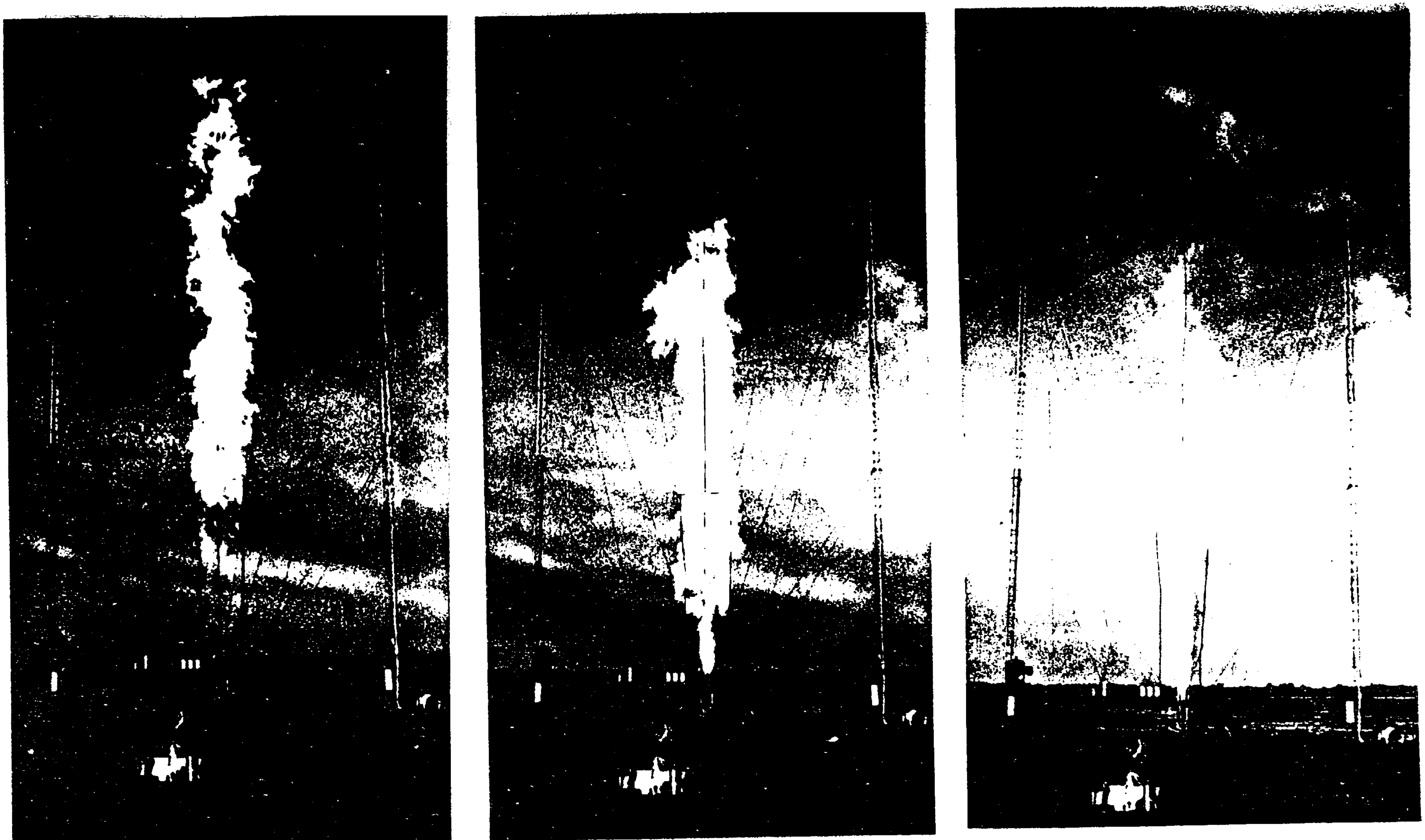
Figure 8 Small Scale Spray Geometries and Extinguishment Effectiveness Ratios



(a)

(b)

Figure 9 Jet Flame Extinguished in Test #5 Using Only 40 Liters of Water
(a) Flame Prior to Water Application
(b) Flame Being Extinguished



(a) (b) (c)

Figure 10 Three Photographs Taken During Test #6 - (a) Showing Fire Before Water Application (b) Flame at Time Water is Injected, (c) Steady Burning of the Methane-Water Spray Mixture

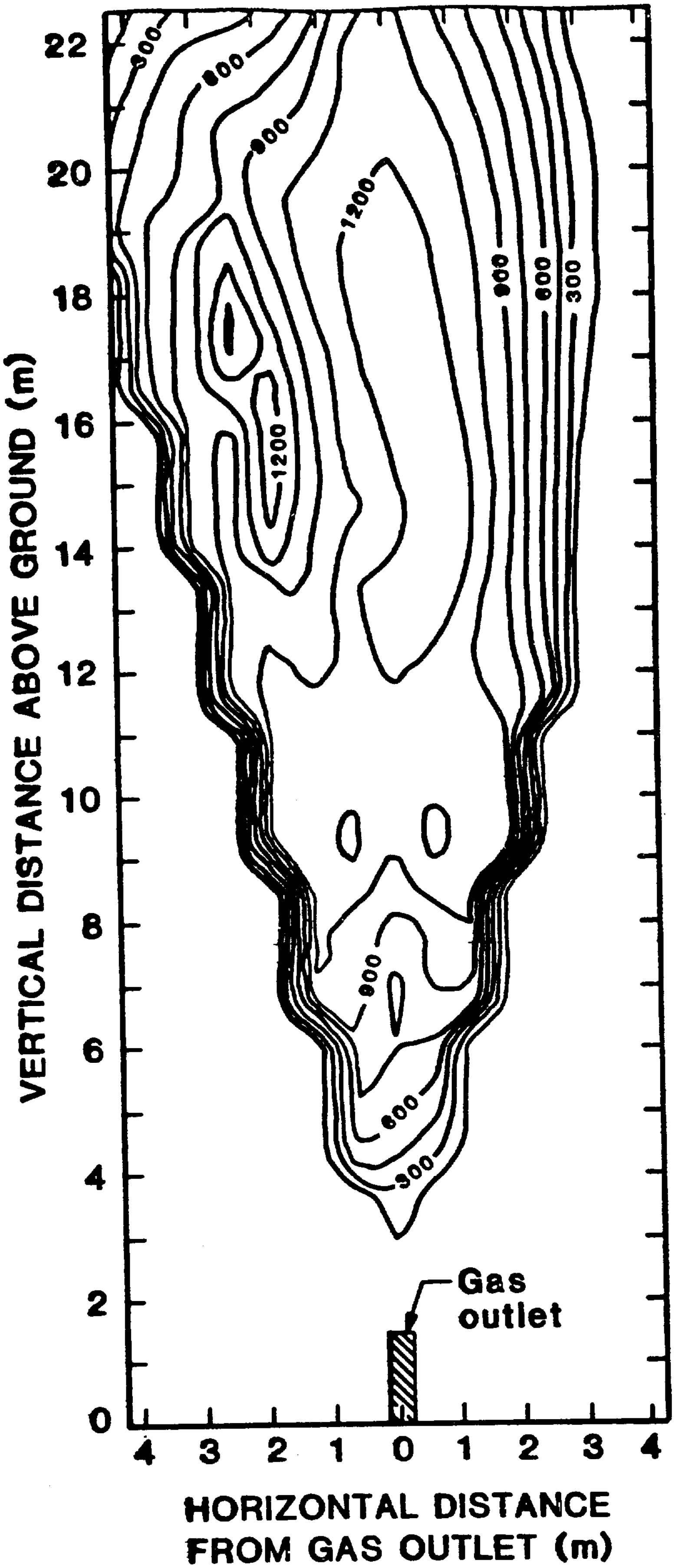


Figure 11 Temperature Contour Plot for Test 6 Prior to Water Application (Contours from 150 °C to 1200 °C with interval of 150 °C, Test Time 17:16:44)

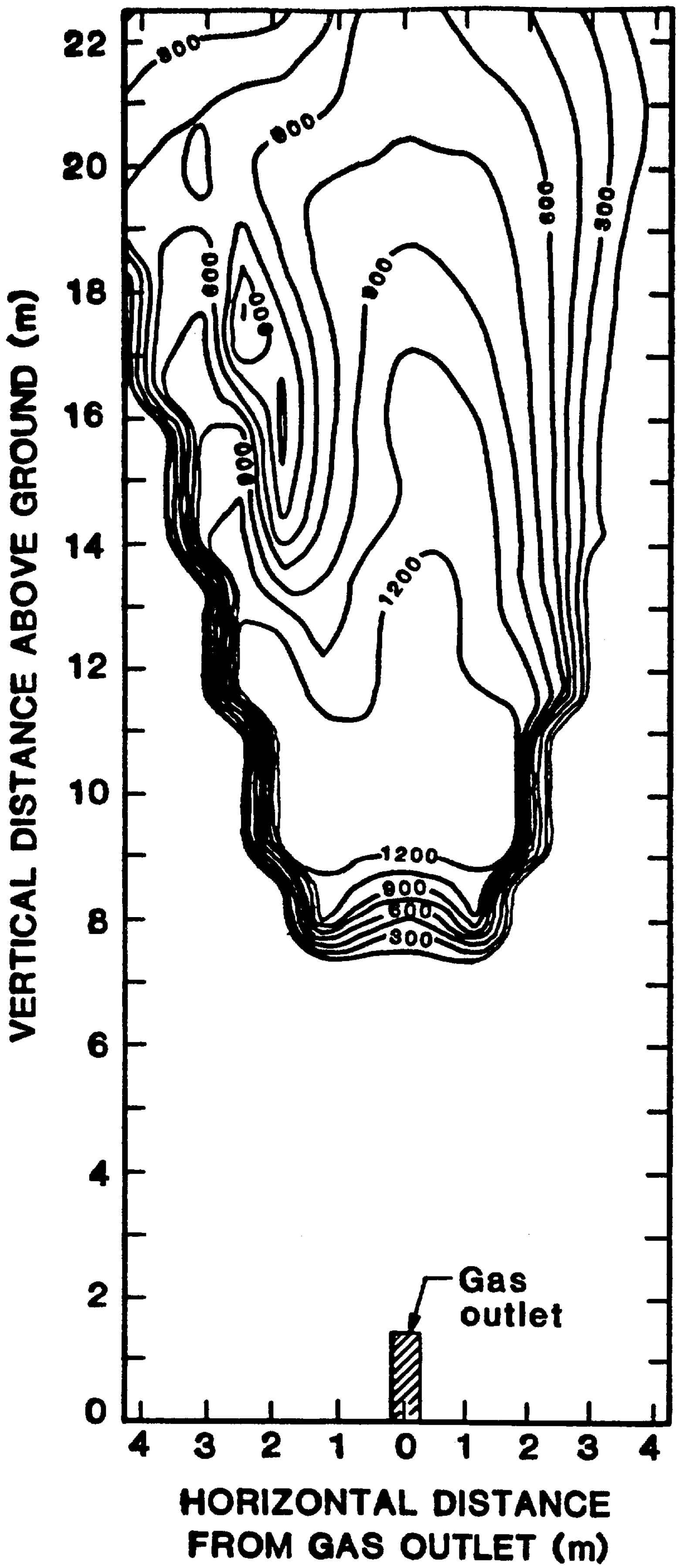


Figure 12 Temperature Contour Plot for Test 6 During Water Application (Contours from 150 °C to 1200 °C with interval of 150 °C, Test Time 17:16:54)

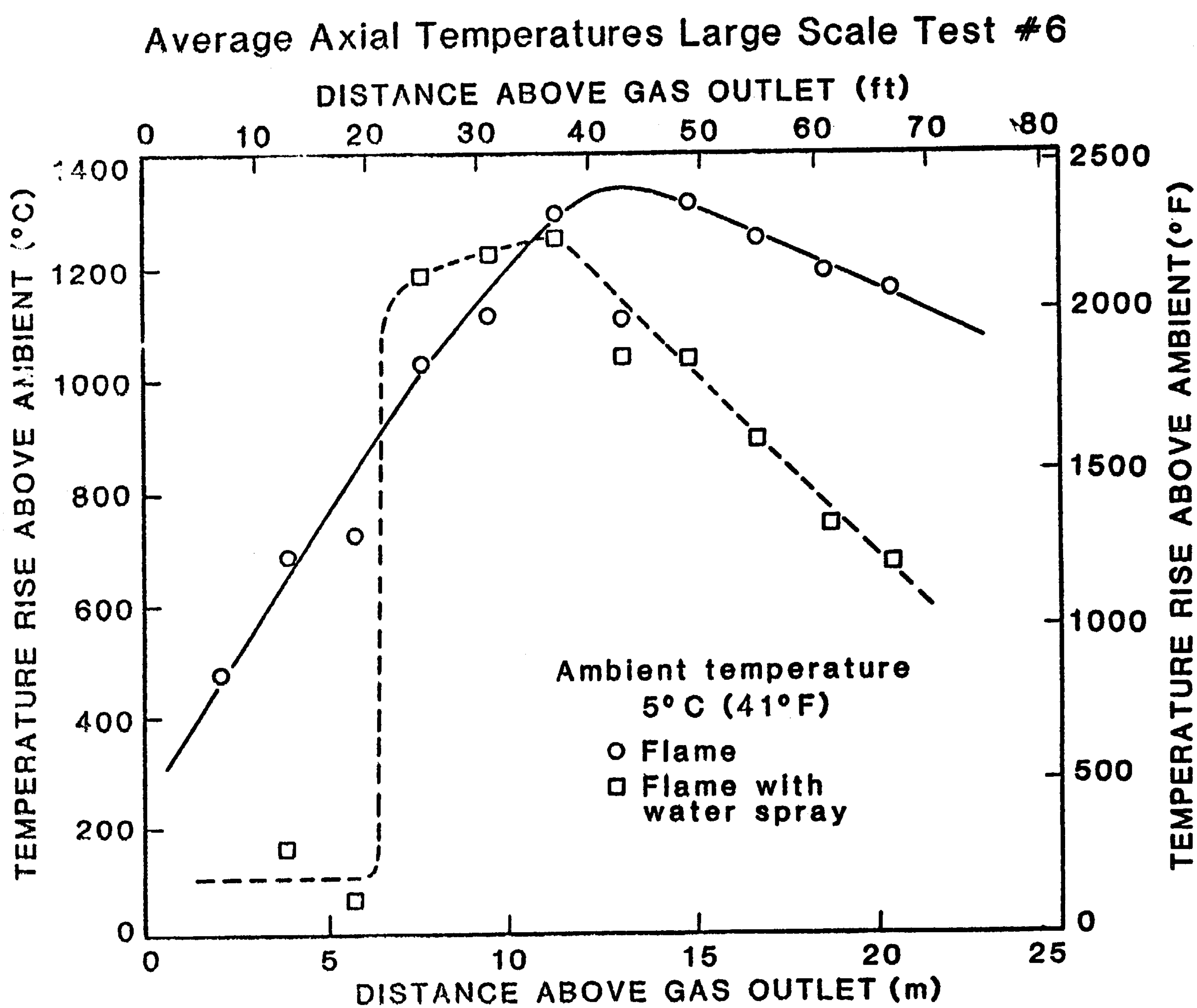
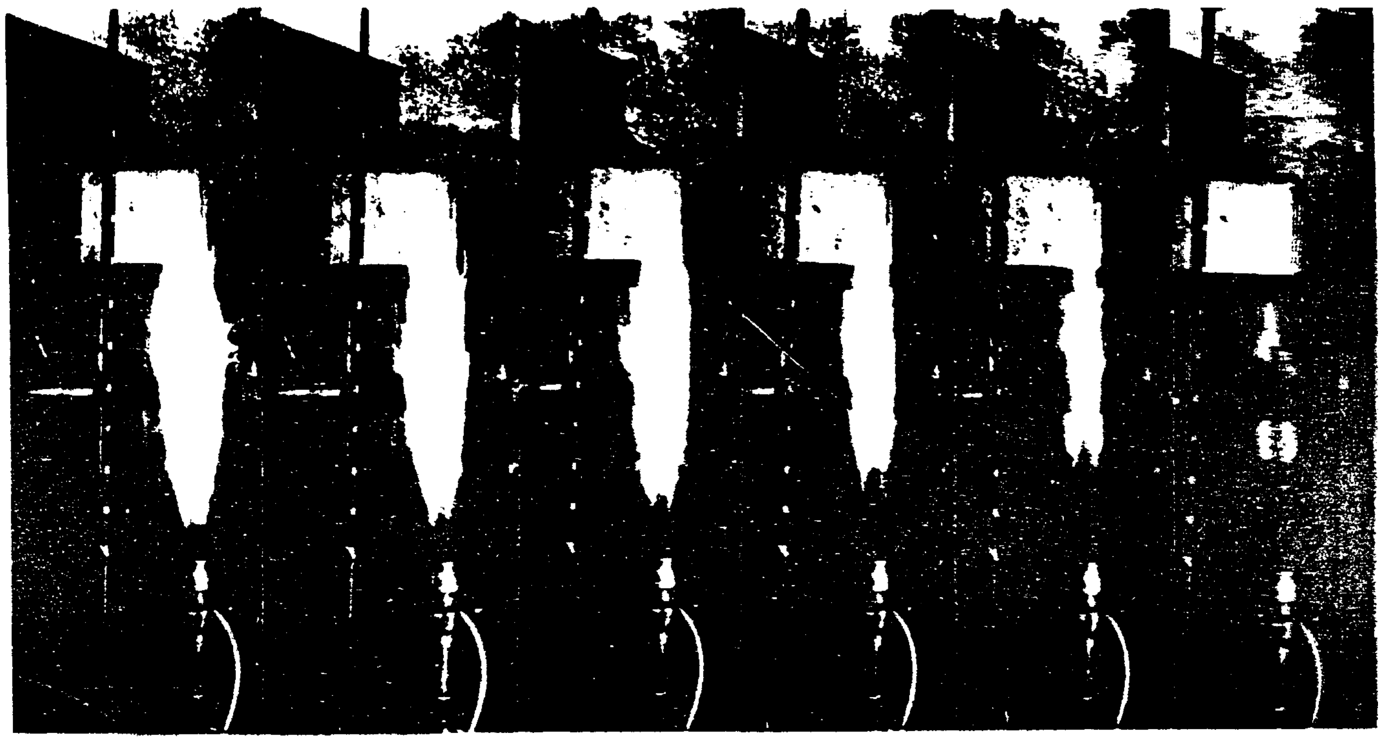


Figure 13 Average Axial Temperatures Before and During Water Spray Injection - Large Scale Test #6



$\dot{m}_{H_2O}/\dot{m}_{C_3H_8}$ 0 0.12 0.23 0.35 0.46 0.58

Figure 14 Effect of Water Spray on Propane Fire (Nozzle Outlet Diameter 18.3 mm)

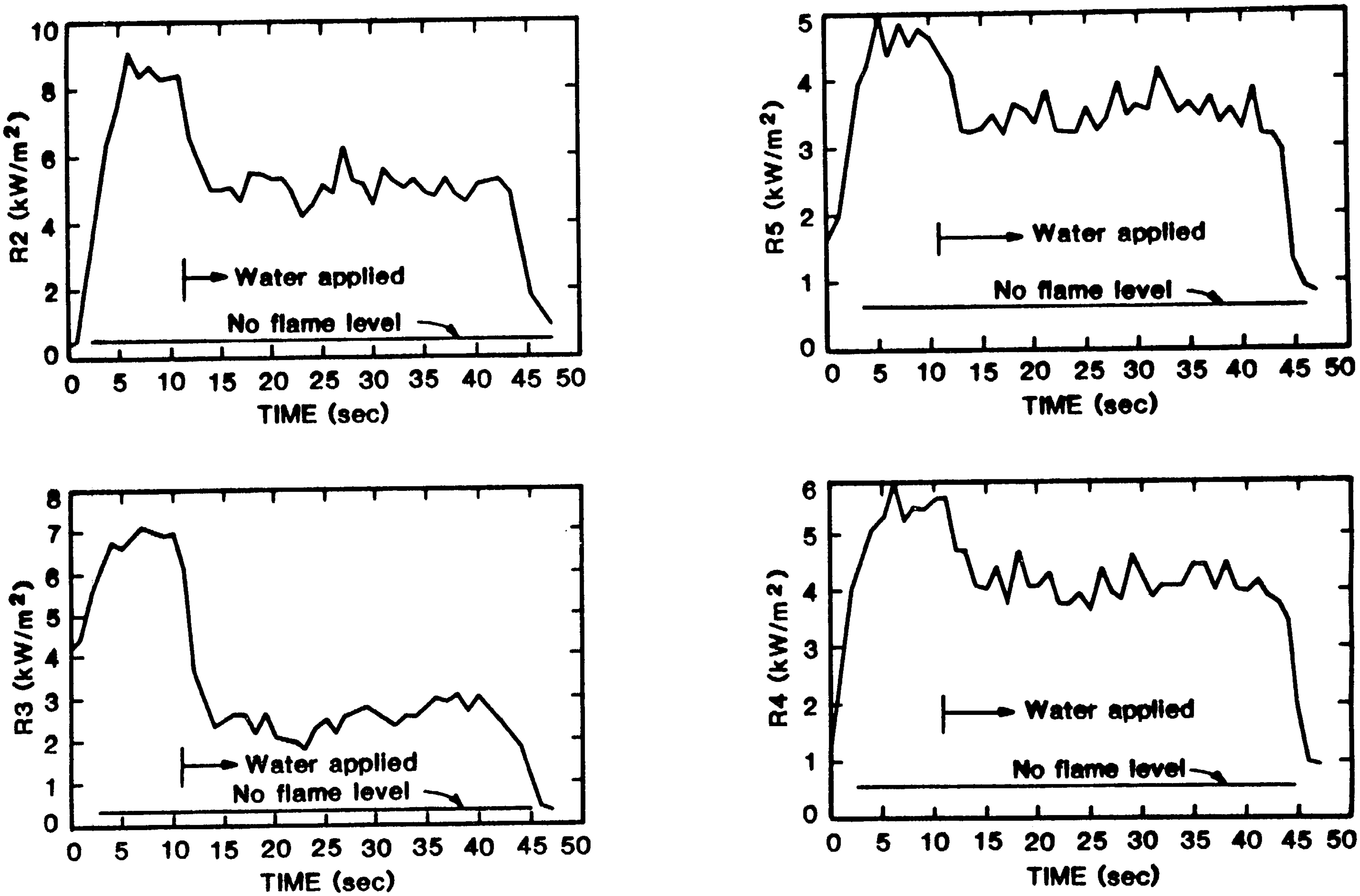


Figure 15 Radiation from Fire Before and During Water Application - Test #6