EFFECTIVENESS OF WATER SPRAY CURTAINS IN DISPERSING LNG VAPOR CLOUDS*

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ABSTRACT

Results from initial experiments to study the effectiveness of water spray curtains in dispersing LNG vapors are presented. The program consisted of outdoor tests with spills of LNG into a 3m x 3m diked area surrounded by water spray nozzles, as well as reduced-scale, model experiments in a wind tunnel simulating massive spills of LNG into a 60m x 60m diked area with spray-curtain protection. The outdoor tests indicated good dispersion performance of both vertical downward and vertical upward sprays. The model experiments of the large, 60m x 60m spills indicated good dilution performance for certain spray conditions using vertical upward sprays; downward sprays had to be inclined toward the dike wall to be effective.

1. INTRODUCTION

LNG pipeline related facilities in the United States are now required[1] to have a "dispersion exclusion zone." Occupied outdoor areas or buildings are prohibited from the dispersion exclusion zone, unless they are part of an LNG facility of the operator. The dispersion exclusion zone begins at the LNG spill impoundment site and extends to the calculated distance where the average vapor concentration in air is 2.5 volume percent according to an assumed accident scenario. In the assumed scenario, vaporization results from the spill caused by rupture of a single transfer pipe which has the greatest overall flow capacity, discharging at maximum potential capacity under certain specified conditions[1]. In calculating the size of the zone, credit can be taken for LNG vapor dispersion control techniques at the facility. Water spray curtains represent one such technique.

This paper presents results from an initial experimental phase to study the effectiveness of water spray curtains in dispersing LNG vapors. The work was conducted by the Factory Mutual Research Corporation (FMRC), with primary assistance from Colorado State University (CSU) who conducted reduced-scale model experiments in a wind tunnel. Other cooperating organizations included Massachusetts Firefighting Academy (MFA), operator of a gas training facility where small-scale LNG spill experiments were performed, and Lawrence Livermore National Laboratory (LLNL), who measured vapor concentrations with specialized equipment in the small-scale spill experiments.

Generally two dispersion mechanisms are considered[2] active with water spray curtains: 1) air entrainment, and 2) spray heating of the cloud. With the former, air entrained in the sprays mixes with, and dilutes, the ground flow of vapor (downward sprays), or vapor entrained from the ground flow is mixed with air entrained above the vapor cloud (upward sprays). With spray heating, the water drops warm the cold vapors to the extent they may become positively buoyant, causing the cloud to rise. In an earlier phase of the current program[2], it was found theoretically that the spray warming effect could be substantial, especially at low wind speeds. However, for the near field, air entrainment is thought to be the primary mechanism.

Water spray dispersal of vapor from LNG spills has been observed in two previous test programs. One program[3] involved a 3.1-m diameter spill pad and upward-facing, fan-spray nozzles located along the downwind centerline of the LNG vapor cloud. The other program[4] employed a crosswind array of upward-facing, fan-spray nozzles downwind of a 2.8-m diameter vaporizing pad. In both cases, significant reductions were observed in the downwind ground-level vapor concentrations when the spray nozzles were actuated.

Some experiments have been conducted on the dispersal of other gases and vapors with water sprays. Moodie[5] has described experiments with downward-directed sprays lined up crosswind behind a point-source release of CO_2 vapor. Substantial reductions in vapor concentrations were associated with the water sprays and there were indications that the inclinations of the spray axes were important. Moore and Rees[6] investigated effects of water sprays as well as steam jets on releases of a number of heavy gases, using both downward and upward spray discharge. They developed semiempirical theories to explain the dilution behavior.

Other theoretical attempts to predict the interaction of water sprays with vapor clouds include that of McQuaid[7], who employed semiempirical air entrainment relations for water sprays operating in quiescent air. Numerical modeling of the interaction has also been attempted, using two-dimensional models; see Zalosh et al[2,8] and Alpert[9]. None of these theories has been adequately tested due to lack of adequate experimental data.

The experimental program described here focussed on the dispersion of LNG vapors overflowing a diked area. One part of the program employed a controlled spill of LNG into a 3m x 3m diked area which was surrounded by upward or downward water sprays; vapor concentrations were measured with and without the sprays activated. Another part of the program, the major one, simulated massive spills of LNG vapor from a 60m x 60m diked area, using a wind tunnel model and an LNG-vapor simulant; a large variety of spray-curtain configurations were investigated in this part of the program. Throughout the program, the experimental results were compared with predictions of a simple entrainment theory[10,11]. The ultimate goal of the program is to establish design guidelines for spray curtains.

2. THEORETICAL EXPECTATIONS

As discussed previously[2], the experiments were guided by a simple entrainment theory for sprays discharging vertically downward in quiescent air, as developed by Heskestad at al[10,11] and verified against actual entrainment measurements.

Using this theory, the average entrained-air velocity in the spray is determined as a function of vertical distance below the spray nozzle for a given water pressure, nozzle diameter and spray cone angle. The distance below the nozzle where the entrained-air velocity has decayed to a particular value, U_g, is readily found along with the associated local spray diameter, d_g.

If the diameter, d_g, is interpreted as the diameter of a conical spray at interception by a ground plane, the total entrained-air flow generated by the spray at ground level may be considered to be approximately the same as that without a ground plane, i.e., $U_g \times \pi d_g^2/4$.

Consider now the application of water sprays to disperse LNG vapor spilling over a dike wall, Figure 1, neglecting for the moment any effect of atmospheric winds on the air entrainment. In order to reduce the concentration of vapors to levels below the lower flammability limit (LFL) without any dispersion by the atmospheric winds, the spray system must be capable of entraining surrounding air at a rate which is some multiple of the spill rate, and it must also be capable of mixing the entrained air with the spill flow. This mixing can occur in the water sprays themselves wherever vapor enters, but perhaps most importantly in the turbulent ground jets from the sprays.

Assuming that the LNG is composed primarily of methane and that a diluted concentration corresponding to the LFL (approximately 5 percent by volume) is desired, then it can be shown that the entrained volumetric flow rate should be at least 52 times the volumetric spill rate of saturated, cold vapor. Representing the volumetric spill rate of saturated vapor per unit diked area as $\dot{q}_v''$ and assuming a square dike shape with a side W, the required volumetric air entrainment rate is $53\ \dot{q}_v'' \cdot W^2$. Dividing this entrainment rate among N conical sprays, each producing an impact circle of diameter d_g on the ground at an entrained-air velocity U_g:

$$N \cdot (\pi d_g^2/4) \cdot U_g = 53\ \dot{q}_v'' \cdot W^2 \quad (1)$$

from which:

$$d_g = 8.21\ (\dot{q}_V''/N\cdot U_g)^{1/2}\ W \quad . \qquad (2)$$

Note that if the diluted concentration is to be 2.5 percent, the number 53 in eq (1) becomes 106, and the number 8.21 in eq (2) becomes 11.6.

It is expected that there is a minimum value of U_g below which the sprays lose their effectiveness. Such a minimum value will exist because of interference by prevailing winds and/or because the entrained air in the sprays must penetrate and mix with the ground flow of heavy vapors. With the value of d_g from eq (2), assuming a minimum value of U_g can be specified, the required nozzle size for downward sprays operated at various water pressures can be determined from entrainment tables[11]. Figure 2 illustrates the relation between required nozzle size, D, and water pressure relative to atmosphere, Δp_w (referenced to unity discharge coefficient), for a 60m x 60m dike and a volumetric spill rate per unit area of $\dot{q}_V'' = 0.029$ m/s, under the assumption that $U_g = 6$ m/s is sufficient and dilution to the LFL is required. A spray-cone total angle of 30 degrees has also been assumed, but the results are not very sensitive to this assumption. The figure is parametric in the number of water sprays, N, which are active in dispersing the flammable vapors. The flow rate per nozzle and the total flow rate can be readily determined from the information in the figure.

For upward sprays one might tentatively speculate that in order to entrain the entire ground flow of vapor, the total volumetric entrainment rate of the sprays, up to the height of the vapor cloud, must exceed the volumetric flow rate in the vapor cloud at the sites of the sprays. The gas velocities within the sprays, upon emerging from the top of the cloud, must also be high enough to carry the vapor to sufficiently high elevations.

3. EXPERIMENTS

The experimental program consisted of small-scale spill experiments with LNG in the field, a brief and intensive effort, and a prolonged reduced-scale model study in a wind tunnel.

3.1 SPILL EXPERIMENTS

The spill experiments were conducted over a two-week period at the Gas

Training Facility at Hopkinton, Massachusetts, operated by Massachusetts Firefighting Academy.

Liquid LNG was spilled into a 3m x 3m diked area ("pit"), as shown in Figure 3. The LNG flow entered through an insulated, 1 1/2-in. stainless steel pipe which was welded to a 6-in. diameter discharge elbow; the expansion in the pipe reduced the velocity of any vapor in the flow. The elbow discharged on a 1m x 1m evaporator pad, consisting of a stainless-steel, embossed-plate heat exchanger carrying high flow rates of water, covered by a stone layer approximately 0.05 m thick which was framed by bricks. Flow rates of LNG were controlled with a calibrated valve in the transfer line from the storage tank; the actual flow rate was checked after an experiment by the timed change in liquid level in the storage tank. For the tests to be reported here, the LNG discharge rates were about 0.45 kg/s, which is considered equivalent to the evaporation rate since there was insignificant accumulation of liquid in the pit. (A few other tests employed 0.1 kg/s.)

Figure 4 presents the layout of gas sensors, wind stations, and a meteorological station operated by LLNL personnel; the figure also indicates the available spray nozzle sites. The local wind direction generally changed so often that it was futile to attempt to spread out the sensors along the direction of plume drift before an experiment, as had been planned; instead, the sensors were arranged in a ring around the pit to ensure that at least some of the sensors would be in the path of the vapor cloud. The sensors were designed by LLNL and were of the infrared type, with the optical path open to the atmosphere; the sensors detected separately methane and ethane-plus-propane.

Twenty-four nozzle sites were prepared in a manifold surrounding the pit for both downward sprays and upward sprays, as included in Figure 4. For the experiments to be reported, the nozzles were of the "swirl" type, having a diameter of 4 mm, a discharge coefficient* of c = 0.89, and producing "full-cone" sprays (Model 14480710, Spraco Products). For downward discharge, the nozzles were installed at an elevation of 0.99 m, which at the test pressure produced a spray impact diameter** of 0.49 m according to laboratory calibrations. In position for upward discharge, the nozzles were within 0.1 m of the ground.

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* The discharge coefficient, c, is defined from the equation:
$Q_w = c\ (\pi D^2/4)(2\ \Delta p_w/\rho_w)^{1/2}$.

** Diameter of circle containing 90% of total water flow.

The actual test pressure was 84 psig; referenced to a nozzle having unity discharge coefficient ($c = 1$ rather than $c = 0.89$), the equivalent pressure is $0.89^2 \cdot 84 = 66$ psig.

Among the 33 regular experiments, a total of 11 were selected for analysis; these were runs during which the wind conditions remained relatively steady. Eight of the 11 runs were conducted with the LNG rate and nozzles described previously. Three representative runs among these eight will be discussed here. The experimental conditions are listed in Table I. Run 10 employed upward sprays, with all 24 nozzles activated. Run 13 employed 12 downward sprays (every other available spray), whereas Run 37 employed 12 upward sprays.

Concentration results from these three runs are presented in Figure 5 in terms of volume percent methane*. At each measurement level (0.1 m, 1 m, 2 m), the concentration plotted at a given time is the maximum indicated by any of the sensors at that level; i.e., the data have been compensated for gross variations in the wind direction. Water was applied during intervals "W." The origin of time is the instant when the valve in the LNG transfer line was opened.

On the basis of the entrainment concepts and theoretical entrainment predictions(11) discussed in Section 2, it had been expected that the 12 downward sprays in Run 13, designed for a ground velocity $U_g = 6$ m/s, would reduce the downwind vapor concentrations to near 5 percent by volume. Reference to Figure 5b indicates that these expectations were met, although the pre-spray concentrations were already quite low. To assess the performance of the upward sprays, the volumetric vapor flow is first estimated as 0.45 (kg/s)/1.8 (kg/m^3) = 0.25 m^3/s cold vapor (112 K). Mixed with air at a pre-spray concentration of about 8 percent, at an assumed approximate mixture temperature of 273 K, the volumetric flow rate of the vapor cloud is estimated at $(0.25 \cdot 273/112)/0.08 = 7.8$ m^3/s. Visually, in the absence of spray, the vapor cloud fanning downwind of the diked area appeared to be about 1 m thick. To the 1 m height, where the sprays were approximately 0.5 m in diameter, each spray is estimated(11) to have entrained** 1.1 m^3/s. In order to entrain the vapor cloud flow of 7.8 m^3/s,

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* According to the supplier, the liquid LNG composition was 87.4% methane, 8.6% ethane, 2.5% propane, 0.6% nitrogen, 0.5% n-butane, and 0.4% iso-butane.

** The entrainment tables in Reference 11 pertain to downward sprays. However, in the near field of the nozzles, the vapor entrainment region for upward sprays, the effects of gravity (at the water pressures considered) are insignificant. Consequently, the results for downward sprays can be used here.

TABLE I

CONDITIONS FOR REPRESENTATIVE SPILL EXPERIMENTS

($\dot{m}$ = 0.45 kg/s; Spraco 14480710 Spray Nozzles)

Run	Spray (Up, Down)	N	Q_w (ℓ/s)	U_w (m/s)
10	Up	24	8.6	1.4
13	Down	12	4.3	0.5
37	Up	12	4.3	0.9

approximately 7.8/1.1 $\approx$7 sprays would have to be active theoretically. For Run 37 in Figure 5c, 12 upward sprays diluted the concentrations to about 2 percent. For Run 10 in Figure 5a, 24 upward sprays diluted the concentrations to about 1 percent. Visually, in both cases, the vapor plume was lofted above the diked area by the sprays; some vapor escaped between adjacent sprays, the vapor escape being less prevalent with 24 sprays than with 12 sprays. The estimated minimum of 7 sprays may be too small, but certainly appears to be of the correct order of magnitude.

As indicated by the on-site meteorological station (Figure 4), the local atmospheric conditions were highly unstable during the spill tests, which may account for the low no-spray vapor concentrations measured.

3.2 WIND TUNNEL STUDY

3.2.1 Foundation

The basis for reduced-scale modeling in this program has been discussed previously[2]. According to Froude Number modeling, dynamic similarity between model and full-scale plume-wind interactions is closely achieved if the vapor density is chosen the same as in full scale and

$$U_M/U_{FS} = (L_M/L_{FS})^{1/2} \quad , \tag{3}$$

where U is the wind velocity; L is a characteristic length of the vapor release geometry; and the subscripts M and FS denote model and full scale, respectively. Fortunately, air entrainment and water drop velocities in modeled water sprays[12] also scale with the square root of the linear-scale ratio, as in eq (3), provided the drop size, d (e.g., mass mean), scales as:

$$d_M/d_{FS} = (L_M/L_{FS})^{1/2} \quad . \tag{4}$$

This allows for simulating by scale modeling both the air/vapor flow and the water spray physics. Some other scaling relationships are:

$$Q_M/Q_{FS} = (L_M/L_{FS})^{5/2} \tag{5}$$

$$\Delta p_{wM}/\Delta p_{wFS} = L_M/L_{FS} \tag{6}$$

$$D_M/D_{FS} = L_M/L_S \tag{7}$$

where Q is the volumetric flow rate of water through the spray nozzles or of the vapor release; Δp_w is the water pressure at the spray nozzles (relative to ambient and referenced to the same discharge coefficient in full scale and model); and D is the diameter of the spray nozzles.

Effects of the subatmospheric temperature of the vapor released have not been considered in these modeling relations. If the model employs a room-temperature LNG-vapor simulant, as in this program, there is a slight distortion in the modeling, which is not considered important. Also, there is no longer a one-to-one relationship between model and full-scale vapor concentrations, but rather[13]:

$$C_{FS} = C_M/[C_M + 0.37\ (1-C_M)] \tag{8}$$

where C is volumetric concentration and where normal room temperature has been assumed for the (isothermal) model flow.

Simulation of atmospheric boundary layers in all their details is a formidable undertaking[14] and partial simulations are normally used. In the present wind tunnel study, turbulent boundary layers approximately representative of a neutrally stable atmosphere and open grassy land were employed.

Wind tunnel modeling of LNG spills according to these principles, but not including water sprays, has been accomplished in several previous programs; see, for example, Neff and Meroney[13], Meroney et al.[15] and Meroney[16].

3.2.2 Facility and Methods

The experiments were carried out in the Environmental Wind Tunnel at Colorado State University, Fluid Dynamics and Diffusion Laboratory, which has a cross section 3.66 m wide and 2.13 m high. A 60m x 60m diked area was simulated on a linear scale ratio of 1:100; hence, the model measured 60cm x 60cm. The full-scale dike height represented in most of the work was 4 m, or 4 cm in the model (sheet steel). Figure 6 is a plan view of the model, together with the sampling grid used for the concentration measurements. The diked model was built into a turntable flush with the floor of the tunnel, which allowed variations in the relative wind direction.

Carbon dioxide, with a small amount of ethane for detection (approximately 1 percent), was used as LNG-vapor simulant (specific gravity of 1.5). Concentrations were usually measured at all 42 points in the grid shown in Figure 6; samples were drawn through plastic tubing into syringes over a 5-minute interval and subsequently analyzed with a gas chromatograph combined with a flame-ionization detector.

Wind speeds, referred to an elevation of 5 m (5 cm in model), were varied over the range 2.2 - 8 m/s (22 - 80 cm/s in the model).

Spray nozzles used were manufactured by Spraco, Inc. and produce "hollow-cone" sprays in the design-pressure range. However, in this program, they were operated at lower pressures, where they produce "full cones." For convenience, the nozzles* have been given letter codes (A, H, I) as identified in Table II. Figure 7 illustrates the various nozzle arrangements examined in the study, not all of which will be discussed here. The central arrow within each arrangement indicates the wind direction. In the downward discharge mode, the spray nozzles were mounted on horizontal manifolds supported on stands. In the upward discharge mode, the nozzles were mounted on a manifold underneath the turntable, the upward-pointing nozzles inserted through clearance holes in the turntable, flush with the top of the turntable.

3.2.3 Early Experiments

A feasibility segment of the experiments involved Nozzle A (Table II), downward or upward discharge, nozzle arrangements A through G (Figure 7, with L_S = 14.7 m full scale), different wind speeds in the range 2.2 - 8 m/s (full scale), water pressures of 0 and 84 psig** (full scale), and an intended LNG (simulant) discharge rate of mostly 180 kg/s (full scale). The discharge rate of 180 kg/s for the 60m x 60m area corresponds to $\dot{q}_v'' = 0.029$ m/s, the value used for Figure 2 and considered representative of peak overflow rates for LNG spills on soil and dike heights in the range 4-6 m[17].

In downward discharge, Nozzle A was placed at an elevation of 14.2 m (full scale), producing an impact diameter on the ground of d_g = 9.8 m (full scale). The combination with nozzle arrangement A (N=12) and a water discharge pressure of 84 psig (0.58 MPa) corresponds to one of the combinations in Figure 2 which had been expected to reduce vapor concentrations to the LFL, or 5 percent by

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* In reference 2 it is pointed out that the model nozzles are likely to produce somewhat larger drop sizes than required for strict modeling according to eq (4). However, it is also argued that strict modeling of drop size is not necessary since air entrainment rates are quite insensitive to drop size.

** This and other full-scale water pressures indicated have been referenced to unity discharge coefficient throughout.

TABLE II

SPRAY NOZZLES

Nozzle	Mfg/Model	Dia(mm)	c	Full Scale Dia(mm)
A	Spraco/19577604	0.46	0.42	46
H	Spraco/19437604	0.30	0.34	30
I	Spraco/18171804	1.02	0.24	102

volume. The measurements indicated values which, disappointingly, were much higher. Later, after the feasibility experiments had been completed, it was discovered that, inadvertently, the actual discharge rate of LNG (simulant) had been considerably higher than the intended rate throughout the early experiments, actually by a factor of 1.82. However, the dilution performance was disappointing even with this realization, an outcome which could not be attributed to deficiencies in the wind tunnel modeling method.

Figure 8 shows some crosswind vapor concentrations at x=90m near ground level from the feasibility experiments, including the downward-spray case discussed in the preceding paragraph. All profiles peak near y=0, the region centrally downwind of the spill area. Without spray, peak concentrations are about 70 percent. With downward or upward sprays, the peak concentrations are only reduced to about 50 percent. None of the other nozzle arrangements appeared to provide better performance per unit flow rate of water. For example, a doubling of the number of nozzles (arrangement B, Figure 7) reduced the peak concentration for downward sprays from about 50 to about 25 percent, while that for upward sprays hardly changed at all.

Smoke was sometimes introduced in the discharge flow of LNG-vapor simulant to make the flow visible, using a commercial oil smoke generator. With the aid of this technique, it appeared that the reason for the poor dilution performance, as far as the downward sprays were concerned, was the apparent inability of the air entrained in the sprays to mix with the ground flow of heavy vapors. The ground area underneath each spray was practically clear where water was impacting, surrounded by dense smoke, as if the entrained air skipped above the heavy vapor outside the spray impact area, rather than mixing with it. Evidently this was not a problem in the small-scale spill tests (Section 3.1) because of the very dilute state of the LNG vapors as they approached the sprays.

3.2.4 Exploratory Experiments

Next followed an exploratory segment in search of spray-curtain configurations more effective than had been observed in the early experiments. Partial arrays of nozzles were used to expedite the work, using three nozzles on the lee side of the diked area, arrangement J in Figure 7. The water pressure and separation distances of the nozzles from the dike, L_S, were varied. Wind speed and LNG-simulant discharge rate were kept fixed at 3 m/s and 180 kg/s, respectively (full-scale values).

Some experiments employed vertical downward sprays, Figure 9a (L_n= 14.9 m, H_S = 14.2 m, L_S = 14.7, 4.9 m). Others employed downward inclined sprays, Figure 9b (L_n = 14.9 m, H_S = 14.2 m, L_S = 21.0 m), which had been expected to produce good mixing between vapor and entrained air. Finally, some experiments were conducted with vertical upward sprays, Figure 9c (L_n = 14.9, H_S = 0, L_S = 14.7, 4.9 m). The main interest in conjunction with vertical upward and downward sprays was to investigate effects of spray proximity to the dike wall.

In brief, there was little effect on the downwind vapor concentrations from reducing the distance of the nozzles from the dike wall by a factor of three, for both upward and downward sprays. At 84 psig water pressure, both the vertical downward and downward inclined sprays produced local downwind concentrations (x=90 m) near ground level of about 12 percent, while that for vertical upward sprays was about 35 percent (versus about 40 percent without spray). Quadrupling the water pressure to 336 psig had the effect of reducing the concentration for the vertical downward sprays to about 5 percent, whereas that for the downward inclined sprays dropped to about 1 percent and that for vertical upward sprays dropped to about 2 percent.

From this exploratory study, two spray configurations appeared very promising at sufficiently high water pressure: downward inclined sprays and vertical upward sprays. It was of immediate interest to confirm the good performance at 336 psig in full-perimeter versions of the partial spray curtains, i.e., nozzle arrangement B (Figure 7) for vertical upward sprays (L_n = 14.9 m, H_S = 0, L_S = 14.7 m) and nozzle arrangements K for downward inclined sprays (L_n = 14.9 m, H_S = 14.2 m, L_S = 21.0 m). The former configuration with upward sprays will be referred to as configuration I, and the latter configuration with downward inclined sprays will be referred to as configuration IV. Figure 10 presents results of maximum* ground-level concentrations at x=90m (60 m from dike) as a function of wind speed for the two configurations, compared with no-spray data. The performance is good throughout the range of wind speeds examined.

*Actually the average of readings over 15 m $\leq$ y $\leq$ 15 m, which always included the maximum reading.

3.2.5 Recent Experiments

Recent experiments in the wind tunnel have investigated effects of water pressure, vapor rate, combinations of dike height/storage tank, and nozzle size.

Table III lists the spray configurations investigated, including configurations I and IV studied in the preceding work. In addition to configurations with Nozzle A (D=46mm), there are configurations with the larger, Nozzle I (D=102mm) and the smaller, Nozzle H (D=30mm, see Table II).

Experimental conditions and key results are listed in Table IV. In this table, Δp_w represents the water pressure above ambient (referred to unity discharge coefficient); $\dot{q}_w$ is the volumetric discharge rate of water per nozzle; α is the total spray-cone angle; and $\dot{m}$ is the total mass discharge rate of LNG vapor. Furthermore, C represents the maximum volumetric vapor concentration at ground level 60 m downwind of the dike wall; actually C is the average of the maximum reading at this downwind distance and the readings 15 m on either side, laterally, of the sampling point having the maximum reading. A parameter derived from the maximum concentration and the test conditions is listed in the last column, $N\dot{m}_w C/\dot{m}$; here, $\dot{m}_w$ is the mass rate of water per nozzle, such that $N\dot{m}_w$ is the total mass rate of water discharged. This parameter is an indicator of the effectiveness of the water spray; the lower its value, the greater is the dilution achieved for a given water supply.

Two of the columns in Table IV show the combination of dike height ("Dike Ht") and storage tank ("Stor. Tank") employed. Many runs were conducted with a 4 m high dike and no storage tank, as in all previous work. Some runs were conducted with the combinations illustrated in Figure 11.

Runs 108-112 investigated the effect of water pressure for the upward sprays in configuration I. Runs 134-138 comprised a similar investigation for the downward inclined sprays in configuration IV. In both cases, there is a break to lower values of the effectiveness parameter, $N\dot{m}_w C/\dot{m}$, near a water pressure of 336 psi, the condition found effective in previous work.

The actual dilution performance in Run 137, corresponding to a concentration of about 1.5 percent, can be compared to the predicted performance based on the simple entrainment theory(11). The value $U_g = 7.8$ m/s is determined from that theory for the conditions of the experiment, which together with N=20, $d_g = 9.8$ m, $\dot{q}_V'' = 0.029$ and W = 60 m lead to a predicted concentration of 2.4 percent (cf. eqs (1), (2) and associated discussion). It is concluded that the

TABLE III

SPRAY CURTAIN CONFIGURATIONS IN RUNS 108-153

Spray Config.	Nozzle	D(mm)	Spray Orientation	Nozzle Arr.	N	L_s(m)	H_s(m)	L_n(m)
I	A	46	Vert. Up	B	24	14.7	0	14.9
II	I	102	"	"	"	"	"	"
III	"	"	"	A	12	"	"	29.8
IV	A	46	Down-Incl.45°	K	20	21.0	14.2	14.9
V	"	"	"	I	16	"	"	"
VI	"	"	"	H	12	"	"	"
VII	I	102	"	K	20	18.2	10.2	"
VIII	"	"	"	I	16	"	"	"
IX	H	30	"	H	12	34.0	24.0	22.2

TABLE IV

EXPERIMENTAL CONDITIONS AND "MAXIMUM" VOLUMETRIC GROUND-LEVEL CONCENTRATIONS (C) MEASURED 60 m DOWNWIND OF 60 m x 60 m DIKE IN RUNS 108-153 (U_w = 3.0 m/s)

Run	Spray Config.	D(mm)	N	Δp_w (psi)	$\dot{q}_w$ (ℓ/s)	Approx. α	$\dot{m}$ (kg/s)	Dike Ht(m)	Stor. Tank	C	$\frac{N\dot{m}_w C}{\dot{m}}$
108	I	46	24	119	67	38	180	4	None	0.050	0.45
109	"	"	"	168	79	"	"	"	"	0.092	0.97
110	"	"	"	238	94	"	"	"	"	0.040	0.50
111	"	"	"	336	112	"	"	"	"	0.022	0.33
112	"	"	"	475	133	"	"	"	"	0.0106	0.19
113	"	"	"	0	0	"	"	"	S	0.27	-
114	"	"	"	336	112	"	"	"	"	0.0114	0.17
115	"	"	"	0	0	"	90	"	None	0.19	-
116	"	"	"	336	112	"	"	"	"	0.0040	0.12
117	"	"	"	0	0	"	127	"	"	0.29	-
118	"	"	"	336	112	"	"	"	"	0.0062	0.13
119	"	"	"	0	0	"	255	"	"	0.50	-
120	"	"	"	336	112	"	"	"	"	0.020	0.21
121	"	"	"	0	0	"	360	"	"	0.62	-
122	"	"	"	336	112	"	"	"	"	0.028	0.21
123	"	"	"	0	0	"	180	8	M	0.24	-
124	"	"	"	336	112	"	"	"	"	0.0111	0.17
125	"	"	"	0	0	"	"	16	L	0.14	-
126	"	"	"	336	112	"	"	"	"	0.0138	0.21
127	II	102	"	42	195	51	"	4	None	0.056	1.46
128	"	"	"	59	231	"	"	"	"	0.0148	0.46
129	"	"	"	84	276	39	"	"	"	0.0138	0.51
130	"	"	"	119	328	"	"	"	"	0.0128	0.56
131	III	"	12	168	390	"	"	"	"	0.0116	0.30
132	"	"	"	238	464	"	"	"	"	0.0132	0.41
133	"	"	"	299	520	"	"	"	"	0.0113	0.39
134	IV	46	20	119	67	38	"	"	"	0.072	0.54
135	"	"	"	168	79	"	"	"	"	0.038	0.33
136	"	"	"	238	94	"	"	"	"	0.024	0.25
137	"	"	"	336	112	"	"	"	"	0.0149	0.19
138	"	"	"	475	133	"	"	"	"	0.0121	0.18
139	"	"	"	336	112	"	"	"	S	0.0194	0.24
140	"	"	"	"	"	"	90	"	None	0.0056	0.14
141	"	"	"	"	"	"	127	"	"	0.0099	0.17
142	"	"	"	"	"	"	255	"	"	0.026	0.23
143	"	"	"	"	"	"	360	"	"	0.051	0.32
144	"	"	"	"	"	"	180	8	M	0.0148	0.18
145	"	"	"	"	"	"	"	16	L	0.0189	0.24
146	VII	102	"	42	195	51	"	4	None	0.056	1.21
147	"	"	"	59	231	"	"	"	"	0.042	1.08
148	"	"	"	84	276	39	"	"	"	0.035	1.07
149	"	"	"	119	328	"	"	"	"	0.0179	0.65
150	V	46	16	336	112	38	"	"	"	0.0170	0.17
151	VIII	102	"	59	231	51	"	"	"	0.051	1.05
152	VI	46	12	336	112	38	"	"	"	0.036	0.27
153	IX	30	"	"	48	30	"	"	"	0.043	0.14

actual dilution performance was reasonably consistent with the theoretical performance, once the water pressure was high enough to produce a theoretical entrained-air velocity of U_g = 7.8 m/s. Rough theoretical estimates can also be made for the vertical upward sprays in Run 111, comparing the estimated entrainment rate of the water sprays up to the height of the vapor cloud with the estimated volumetric vapor flow. With a reasonable estimate for the thickness of the cloud from the vertical concentration profiles (1.4 m), together with theoretical entrainment results[11], the theoretical entrainment rate is calculated at roughly the same magnitude as the estimated flow rate in the vapor cloud.

The no-spray runs with storage tanks and different dike heights (Runs 113, 123, 125) indicated significant dilution effects of the new geometries, compared to previous results with a 4m high dike alone. This is seen more clearly in Figure 12a, which is a crosswind plot of vapor concentrations for the no-spray runs. For upward sprays (Runs 114, 124, 126), the new geometries also decreased the concentrations relative to the reference case (Run 111), while for downward inclined sprays (Runs 139, 144, 145), there was little effect compared to the reference case (Run 137). Figures 12b and c compare the range of crosswind vapor concentrations obtained with various dike/tank combinations to respective reference cases for a 4-m high dike alone.

Other notable results are those obtained with Nozzle I. The upward sprays in Run 128 at 59 psi had been expected to dilute the vapor cloud to roughly the same level as did Nozzle A at 336 psi in Run 111. The results confirm this expectation; a further comparison is provided by the crosswind concentration profiles in Figure 13a. The expectation of comparable performance had been based on the assumption that the dilution would depend on the entrainment rate of the water spray to the height of the vapor cloud (Section 2). In the downward inclined mode, the dilution with Nozzle I in Run 147 at 59 psi had been expected to be similar to that with Nozzle A in Run 137 at 336 psi (same predicted entrainment rate and entrained-air velocity near ground level). The comparison is not good, C=0.042 in Run 147 versus C=0.0149 in Run 137; crosswind profiles are compared in Figure 13b. No explanation is yet evident.

Notable results were also achieved with the smaller-diameter, Nozzle H. The configuration in Run 153 had been designed to have the same air entrainment rate (in quiescent surroundings) as the Nozzle A configuration in Run 137, yet at a lower entrained-air velocity near ground level, 4.8 versus 7.8 m/s. The higher value of C measured in Run 153 compared to Run 137 is attributed to the lower entrained-air velocity. Note, however, that the water usage in Run 153, 48 ℓ/s·12 = 576 ℓ/s = 9,130 gpm, is considerably smaller than the water usage in Run 137, some 112 ℓ/s·20 = 2240 ℓ/s = 35,500 gpm, which is also reflected in the superior effectiveness parameter associated with the smaller nozzle in Run 153.

4. FUTURE WORK

It is planned to continue the wind tunnel program. The continuation will first explore buoyancy effects ("heating") caused by the sprays, substituting a cryogenic LNG-vapor simulant (mixture of nitrogen and helium cooled to the boiling temperature of methane) in place of the previously used room-temperature simulant (CO_2). Major objectives of the continuation will be 1) to determine spray configurations and water pressures which provide equivalent dispersion performance (using the room temperature simulant, if justified), 2) to firm up performance-prediction methods, and 3) to establish design guidelines.

5. SUMMARY AND CONCLUSIONS

In the outdoor tests, involving spills of LNG into a 3m x 3m diked area and fairly low no-spray vapor concentrations, the spray curtains performed reasonably close to expectations. Vertical downward sprays diluted the vapor concentrations to levels anticipated from the ratio of the LNG-vapor rate versus the theoretical entrainment rate in quiescent air. Vertical upward sprays lofted the vapor cloud above the diked area, producing low ground-level concentrations downwind; the associated water rates were somewhat higher than the minimum estimated theoretically on the assumption that the total entrainment rate up to the height of the vapor cloud should exceed the total flow rate in the cloud.

The main part of this investigation was carried out on 1:100 model scale in a wind tunnel, simulating massive spills of LNG into a 60m x 60m diked area. A room-temperature LNG-vapor simulant was used (CO_2). First experiments with vertical downward and vertical upward sprays gave disappointing results, with diluted vapor concentrations much higher than had been anticipated. Flow visualization suggested that the main reason for the inferior performance, as far as the downward sprays were concerned, was poor mixing bewtween the air entrained in the sprays and the ground flow of very heavy vapors which prevailed in these simulations of large spills. Subsequently, it was found that inclining the downward sprays 45° toward the dike wall and raising the water pressure improved greatly the dilution performance per unit flow rate of water. Enhanced performance per unit flow rate of water was also observed for the vertical upward sprays at the higher water pressures, but not the vertical downward sprays. Theoretical performance estimates of the kind performed for the outdoor spill tests were quite consistent with experimental results at the elevated water pressures for the two successful spray configurations. Over a range of wind speeds from 2.2 to 8 m/s, diluted volumetric vapor concentrations at 60 m downwind of the dike were not very different from the 2.5 percent limit associated with the "vapor exclusion zone"[1] for either the downward inclined sprays or the vertical upward sprays. However, the water requirements were demanding, some 2,240 ℓ/s (35,500 gpm) at 336 psi pressure for the downward inclined sprays.

Other wind tunnel experiments indicated that storage tanks and increased dike heights had little effect on the dilution performance of the downward inclined and vertical upward spray curtains. With regard to nozzle diameter, substitution of a larger spray nozzle at a reduced water pressure, theoretically having similar entrainment rate and entrained-air velocity in quiescent surroundings compared to the original nozzle and pressure, resulted in similar dilution performance in the case of upward sprays. However, in the case of downward inclined sprays, the substitution resulted in inferior performance, an outcome not yet understood. A smaller spray nozzle, investigated only in the downward inclined mode at 336 psi, produced a surprisingly good dilution performance, about 5 percent by volume at the relatively moderate water rate of 576 ℓ/s (9,130 gpm).

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SYMBOLS

C	volumetric vapor concentration
c	nozzle discharge coefficient
D	nozzle diameter
d	drop diameter
d_g	diameter of spray on impact with ground
H_s	height of spray nozzle above ground
L	characteristic length
L_n	distance between adjacent spray nozzles
L_s	distance of spray nozzle from dike
$\dot{m}$	mass discharge rate of LNG vapor
$\dot{m}_w$	mass rate of water discharge per nozzle
N	number of sprays
Δp_w	water pressure above ambient at spray nozzle (referred to unity discharge coefficient)
Q	volumetric flow rate
$\dot{q}''_v$	volumetric vapor spill rate per unit area
$\dot{q}_w$	volumetric discharge rate of water per nozzle
U	velocity
U_g	theoretical entrained-air velocity at ground level in downward sprays
U_w	wind velocity
W	width of (square) diked area
x,y	Cartesian coordinates
α	total spray-cone angle

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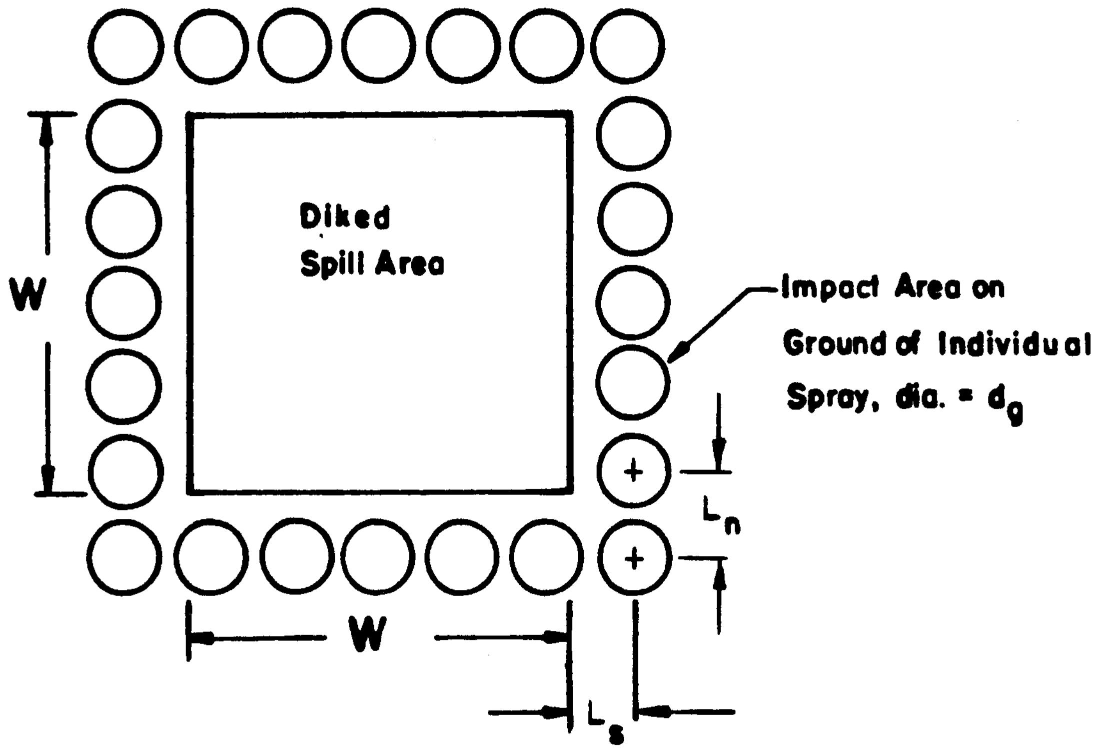

FIGURE 1 WATER-SPRAY NOZZLES SURROUNDING DIKED SPILL AREA.

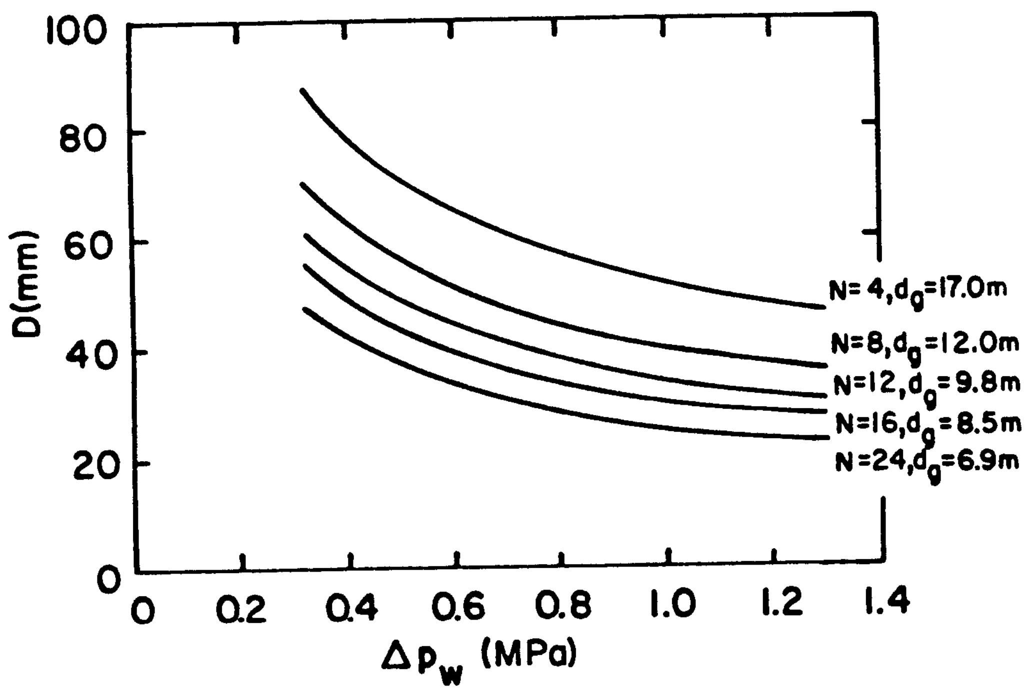

FIGURE 2 THEORETICAL RELATIONS BETWEEN NOZZLE SIZE (D) AND WATER PRESSURE (Δp_w) FOR VARIOUS SPRAY CONFIGURATIONS (N, d_g) WHICH ALL CAN DILUTE BOILOFF FROM 60m x 60m DIKE ($\dot{q}_v'' = 0.029$ m/s) TO THE LFL, ASSUMING $U_g = 6$ m/s.

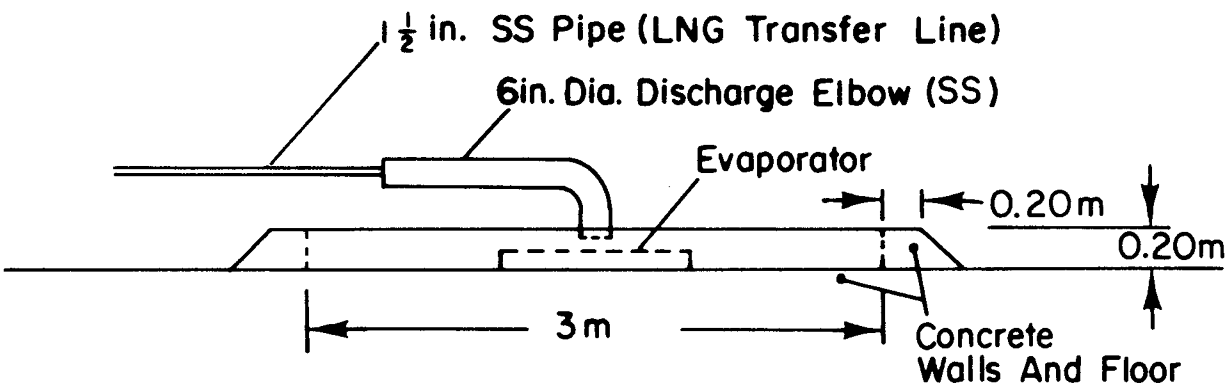

FIGURE 3 SIDE VIEW OF 3m x 3m DIKED SPILL AREA.

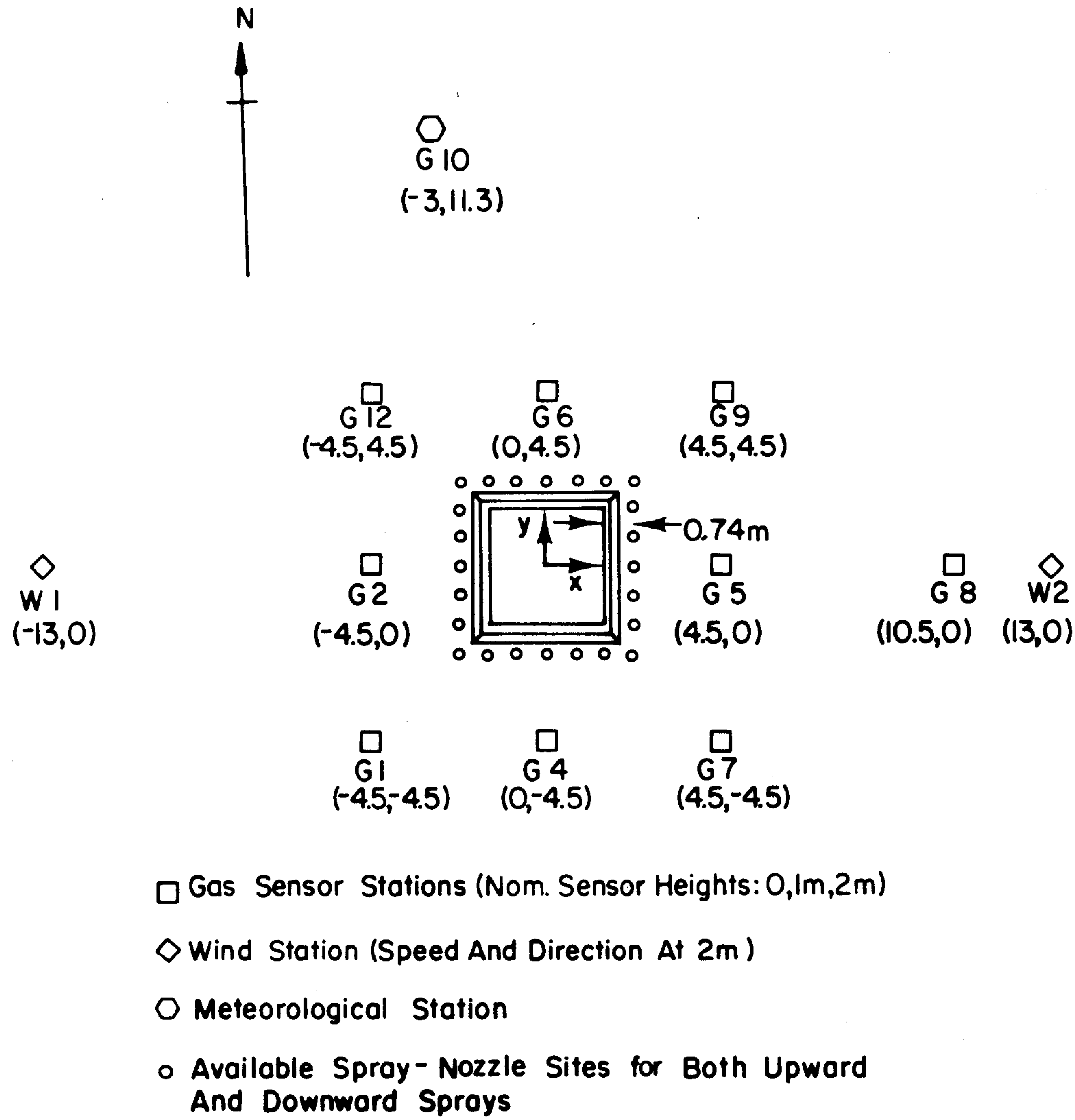

FIGURE 4 LAYOUT OF INSTRUMENTS AND SPRAY NOZZLE SITES. NUMBERS IN PARENTHESES ARE x, y COORDINATES IN UNITS OF m.

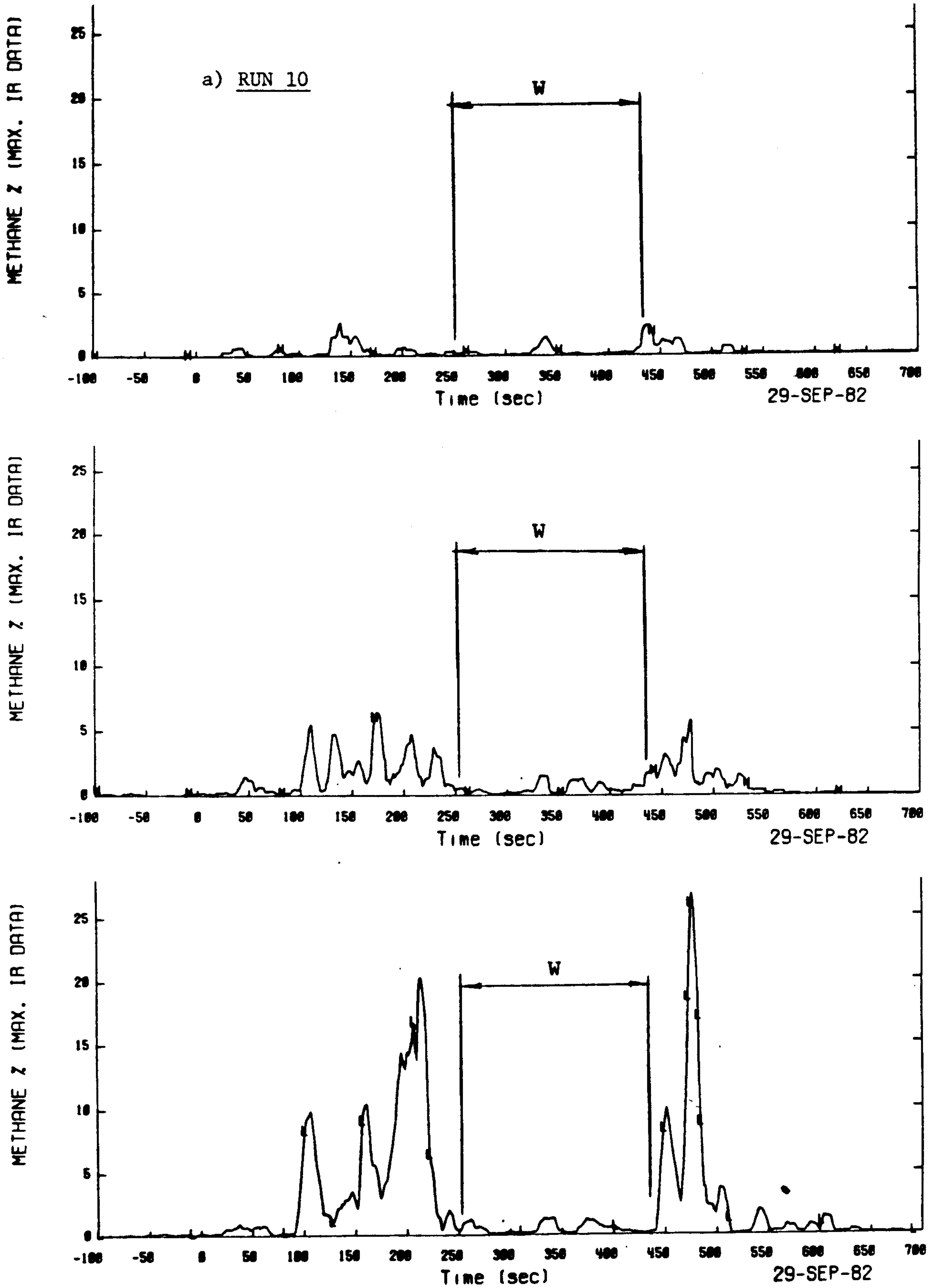

FIGURE 5 MAXIMUM METHANE CONCENTRATIONS 3m FROM DIKE IN SMALL-SCALE SPILL EXPERIMENTS AT ELEVATIONS OF 0.1m (BOTTOM), 1m (MIDDLE) AND 2m (TOP). FULL WATER SPRAY WAS APPLIED IN INTERVAL "W".

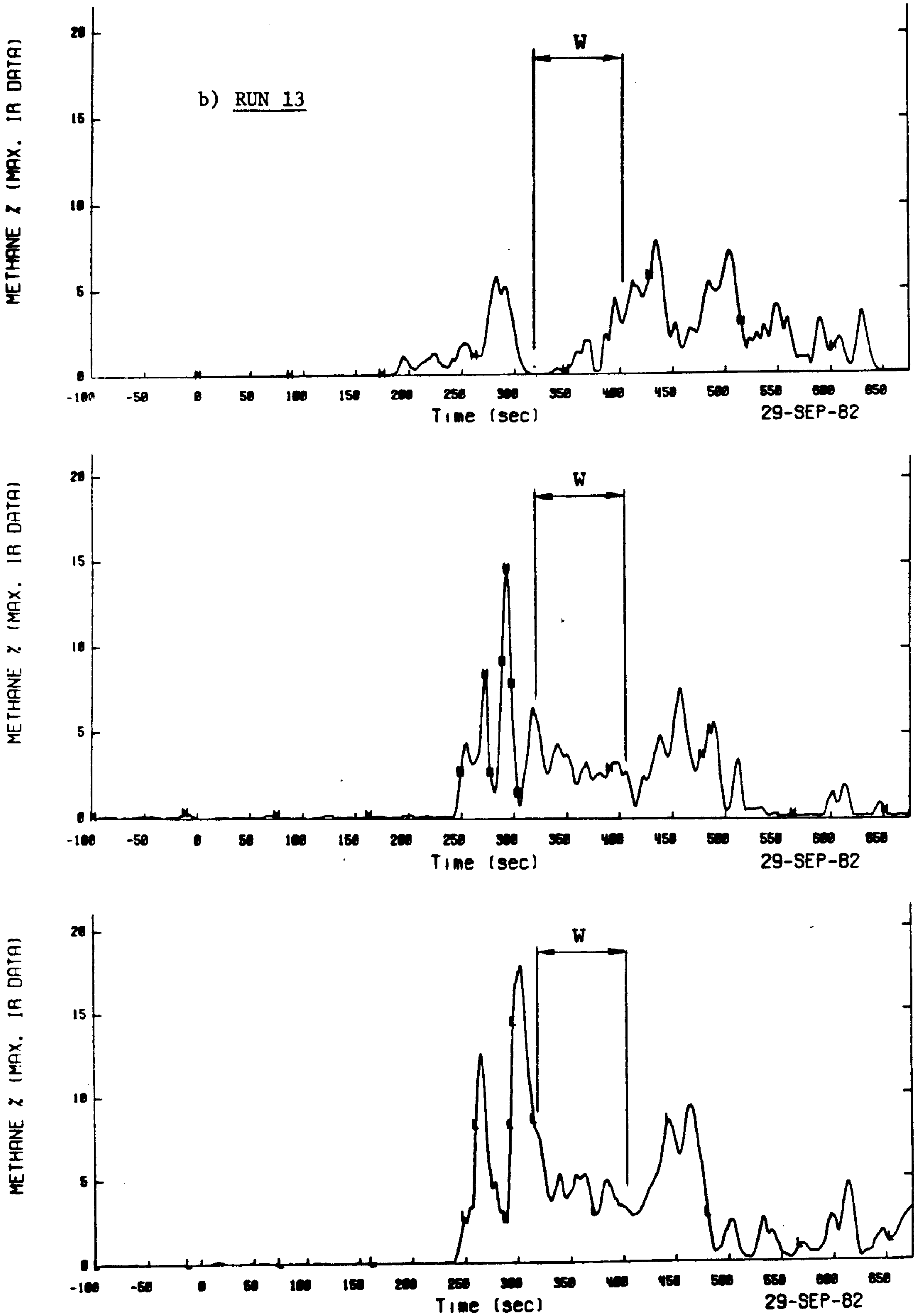

FIGURE 5 (CONTINUED)

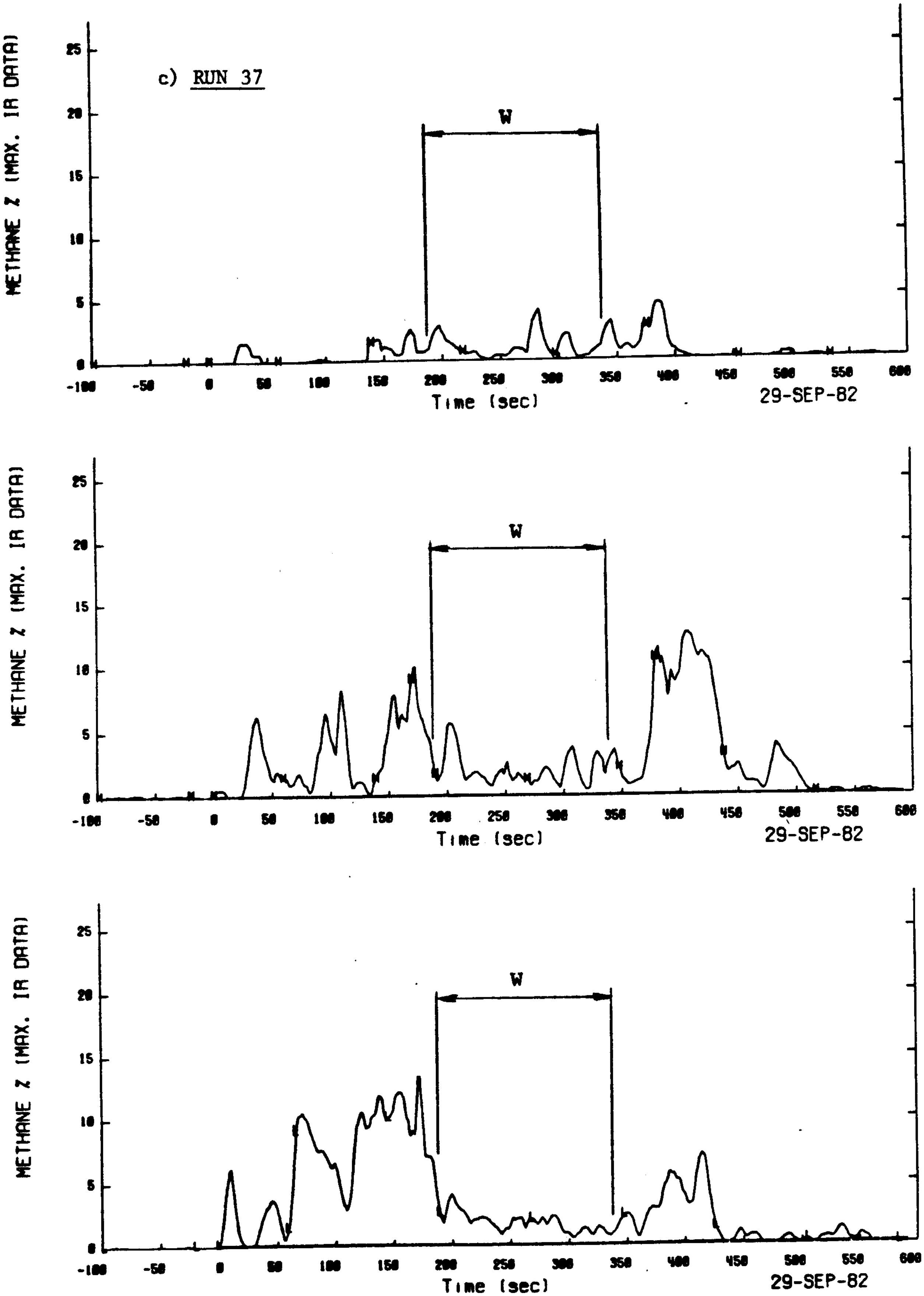

FIGURE 5 (COMPLETED)

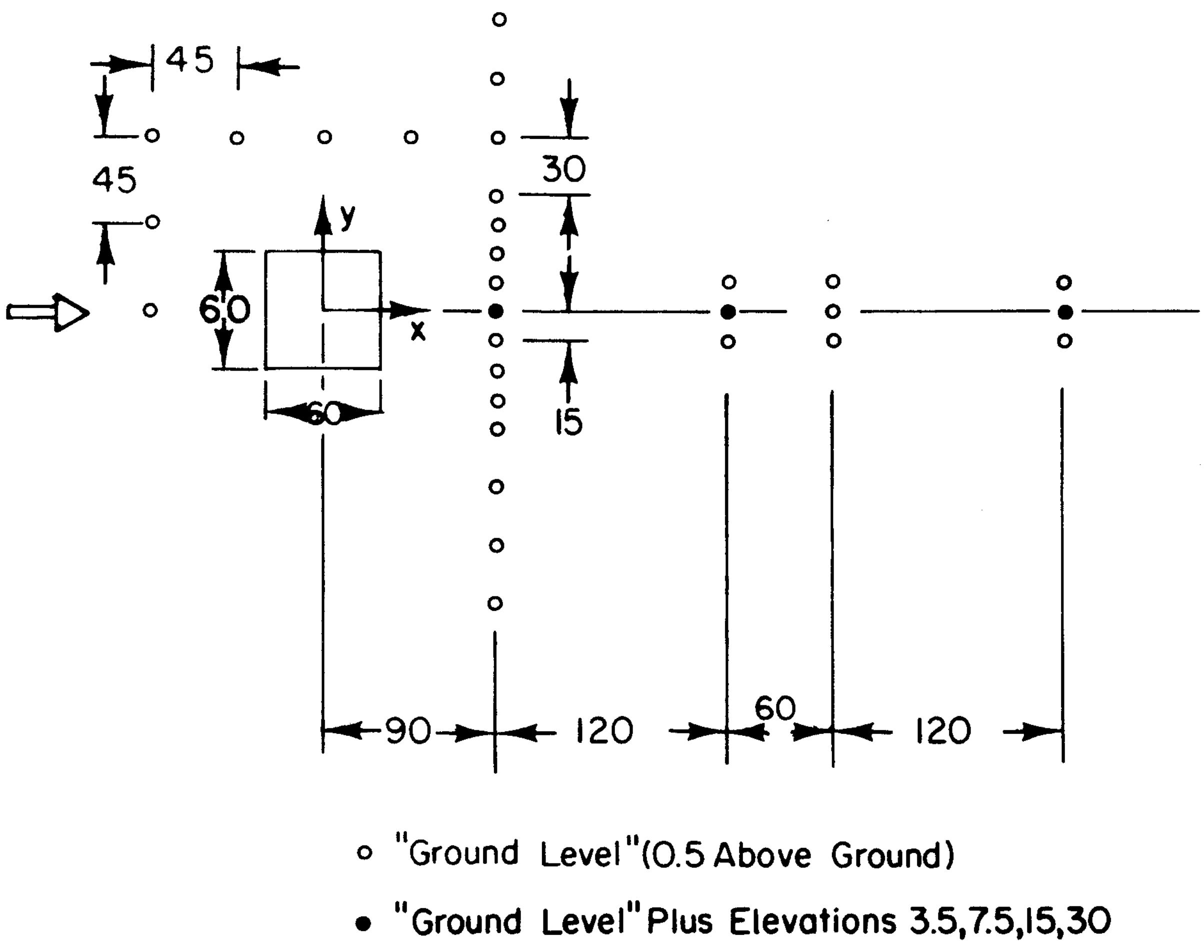

FIGURE 6 SAMPLING GRID FOR CONCENTRATION MEASUREMENTS. ALL DIMENSIONS IN cm (MODEL) OR m (FULL SCALE).

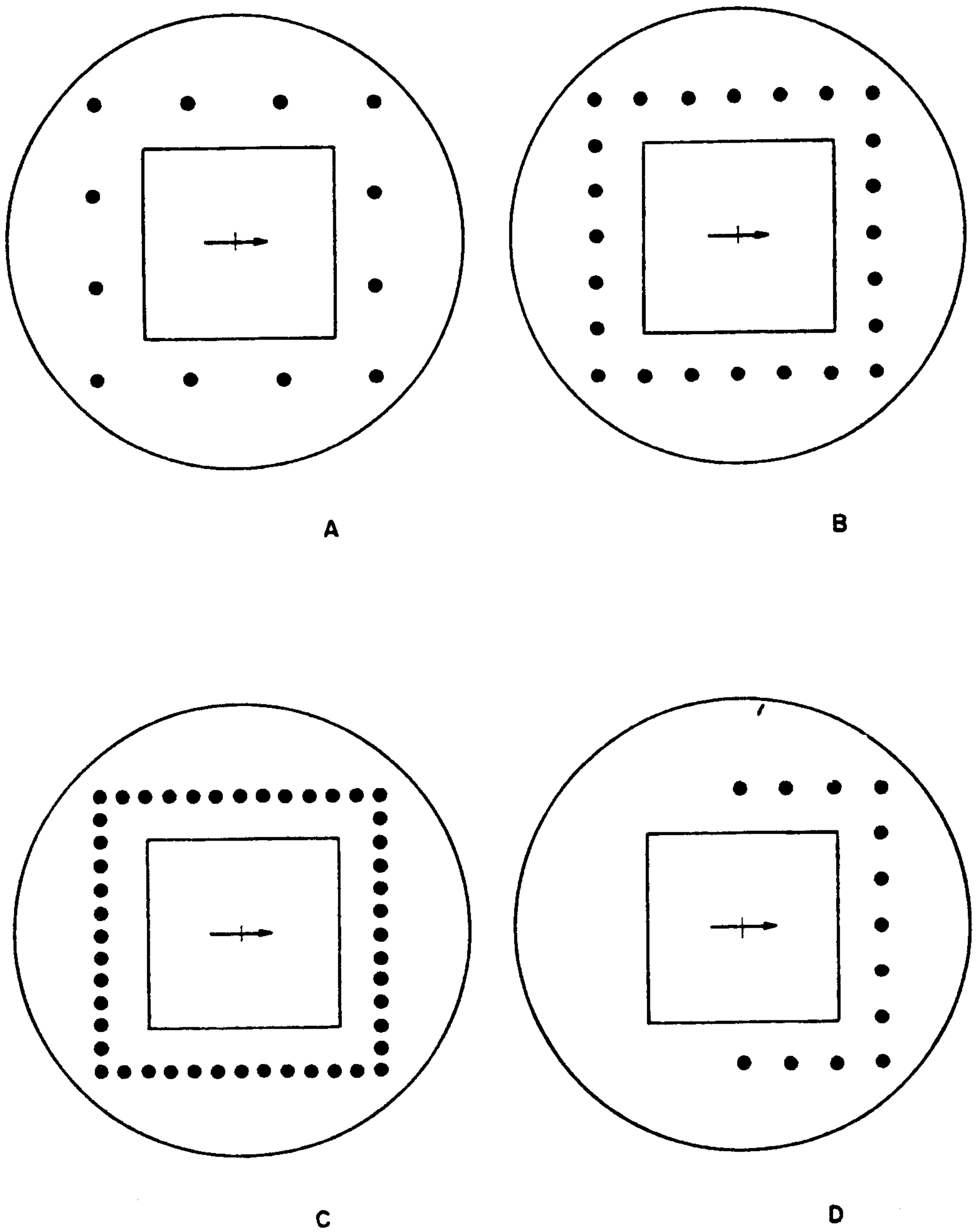

FIGURE 7 NOZZLE ARRANGEMENTS

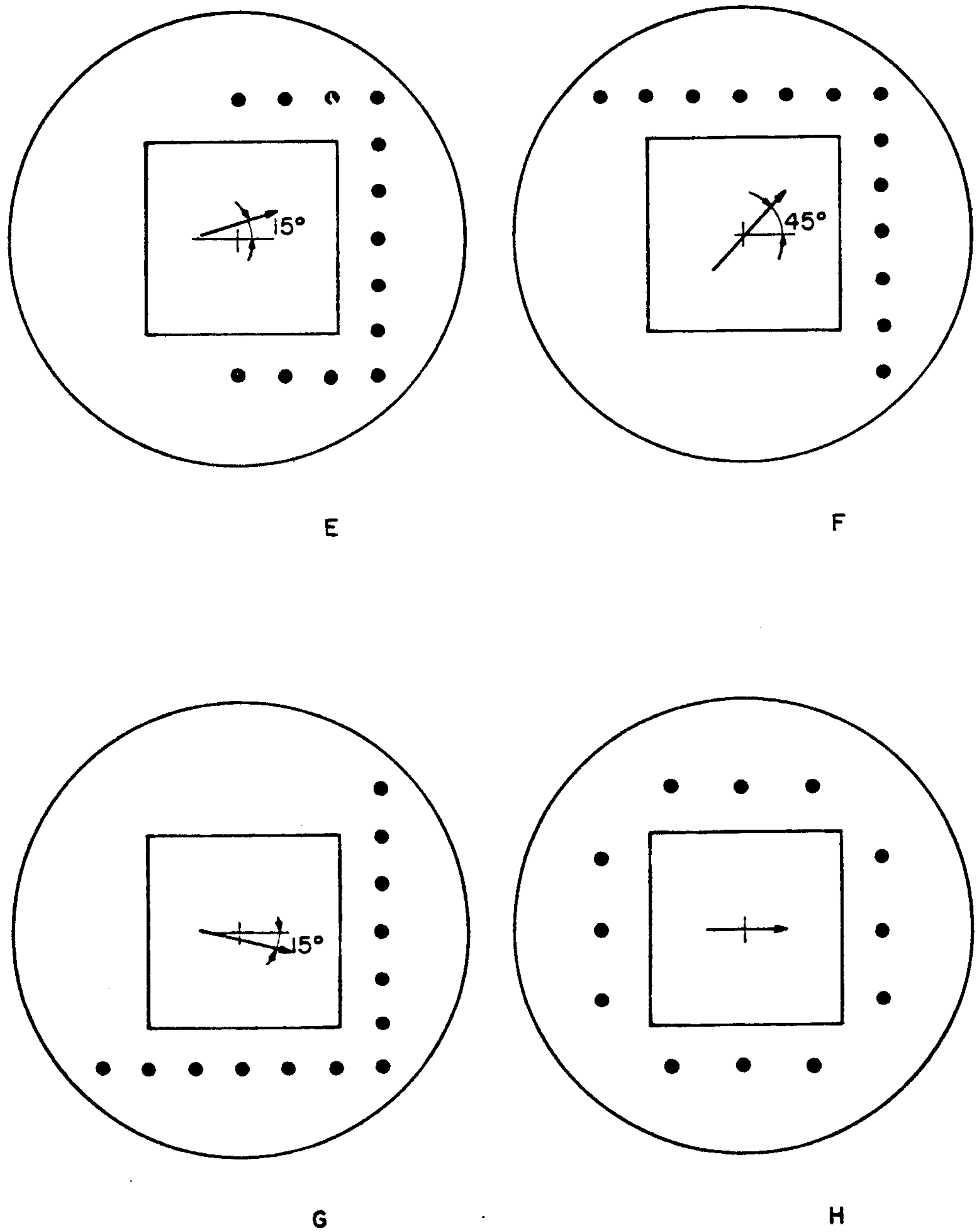

FIGURE 7 (CONTINUED)

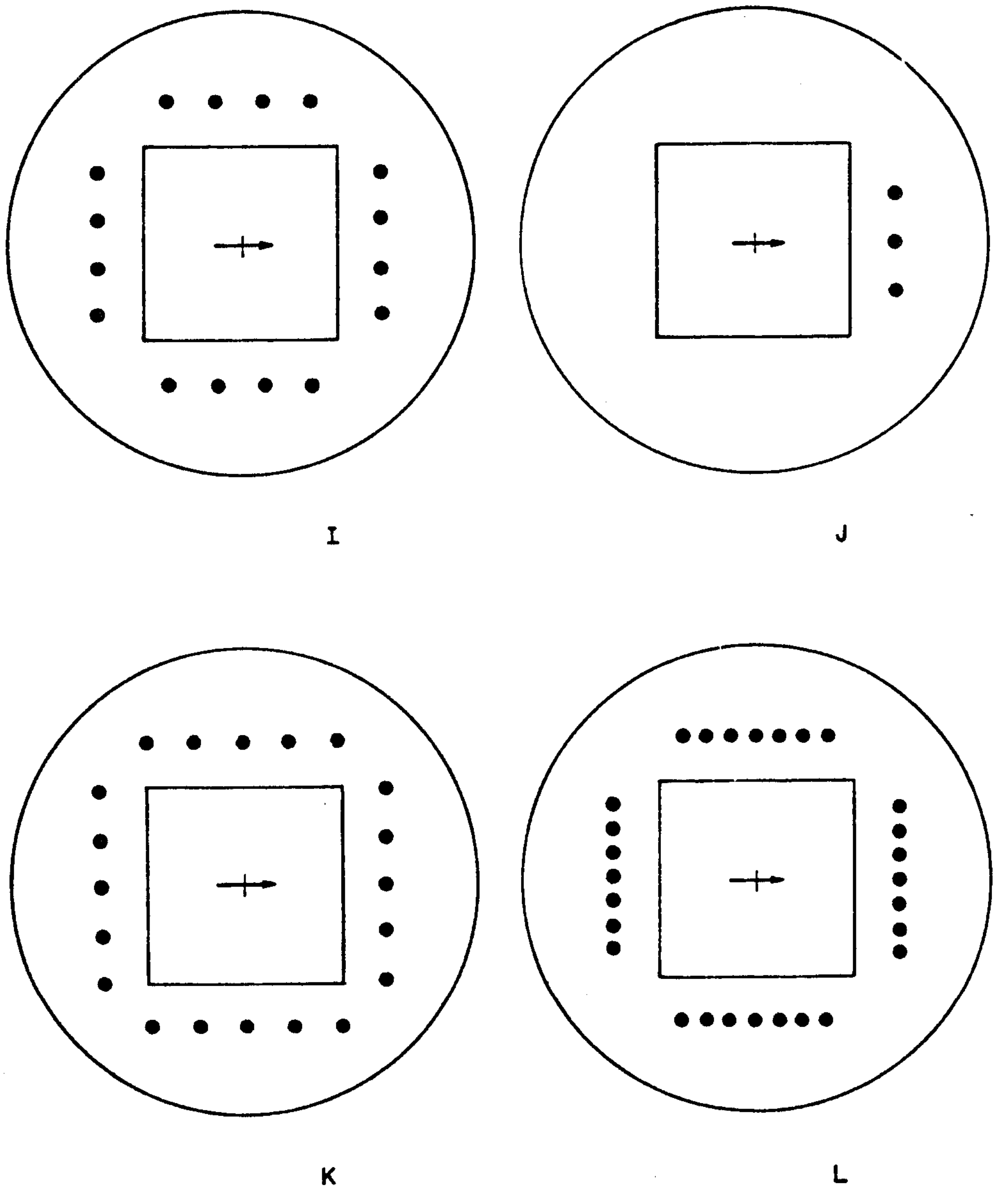

FIGURE 7 (COMPLETED)

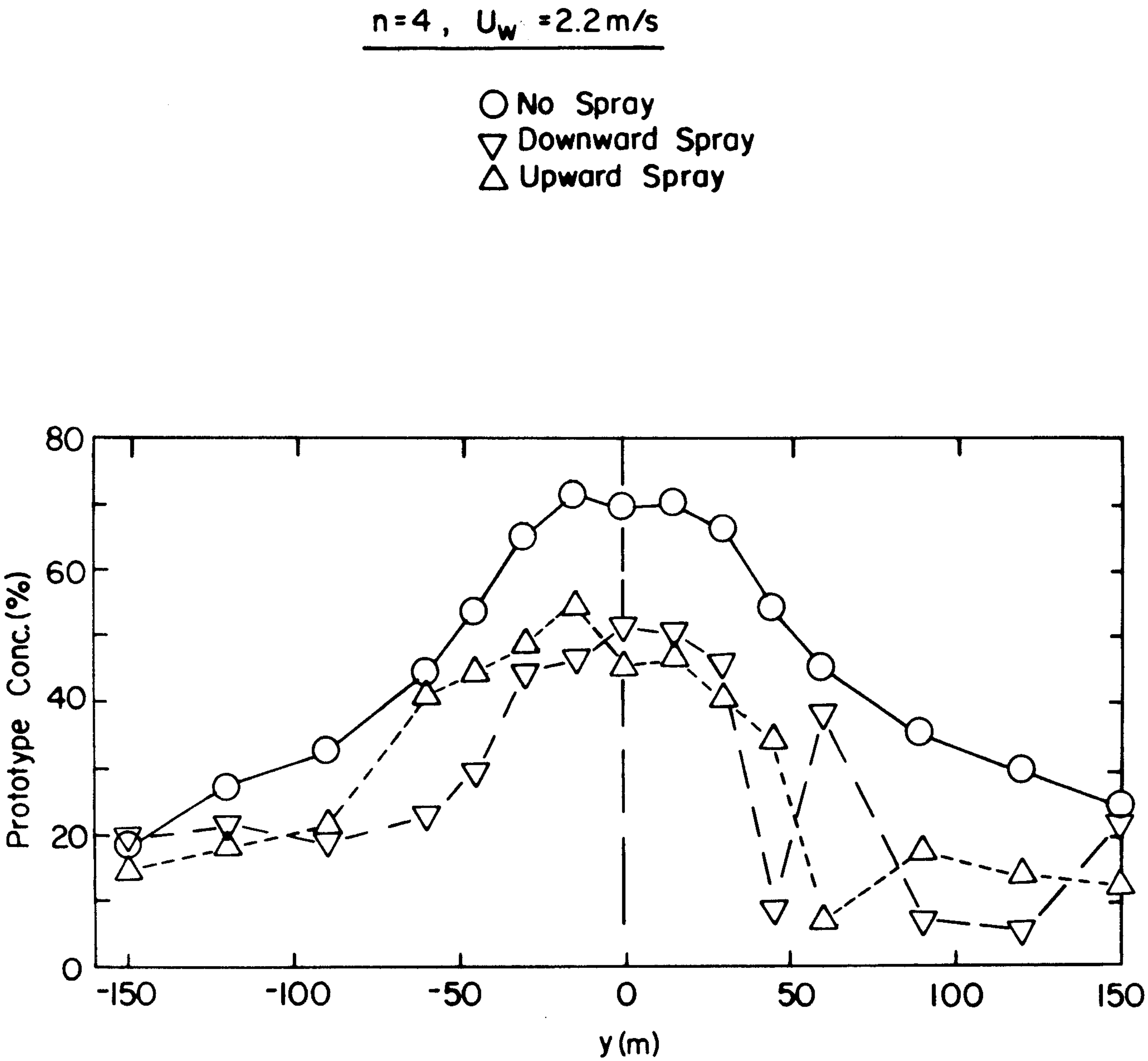

FIGURE 8 CROSSWIND VAPOR CONCENTRATIONS NEAR GROUND AT x = 90m WITH NOZZLE A, ARRANGEMENT A, AND U_w = 2.2 m/s ($\dot{q}_v''$ = 0.053 m/s or $\dot{m}$ = 327 kg/s; d_g = 9.8m; Δp_w = 84 psi).

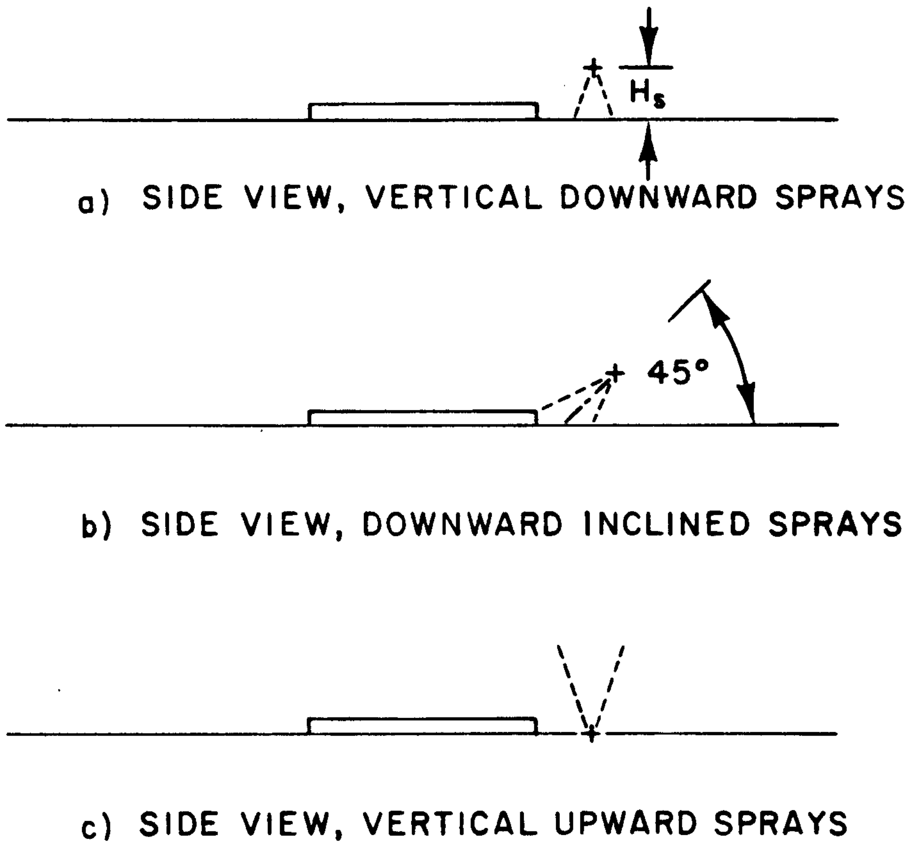

FIGURE 9 PARTIAL SPRAY CURTAINS INVESTIGATED ON LEE SIDE OF DIKE IN EXPLORATORY EXPERIMENTS.

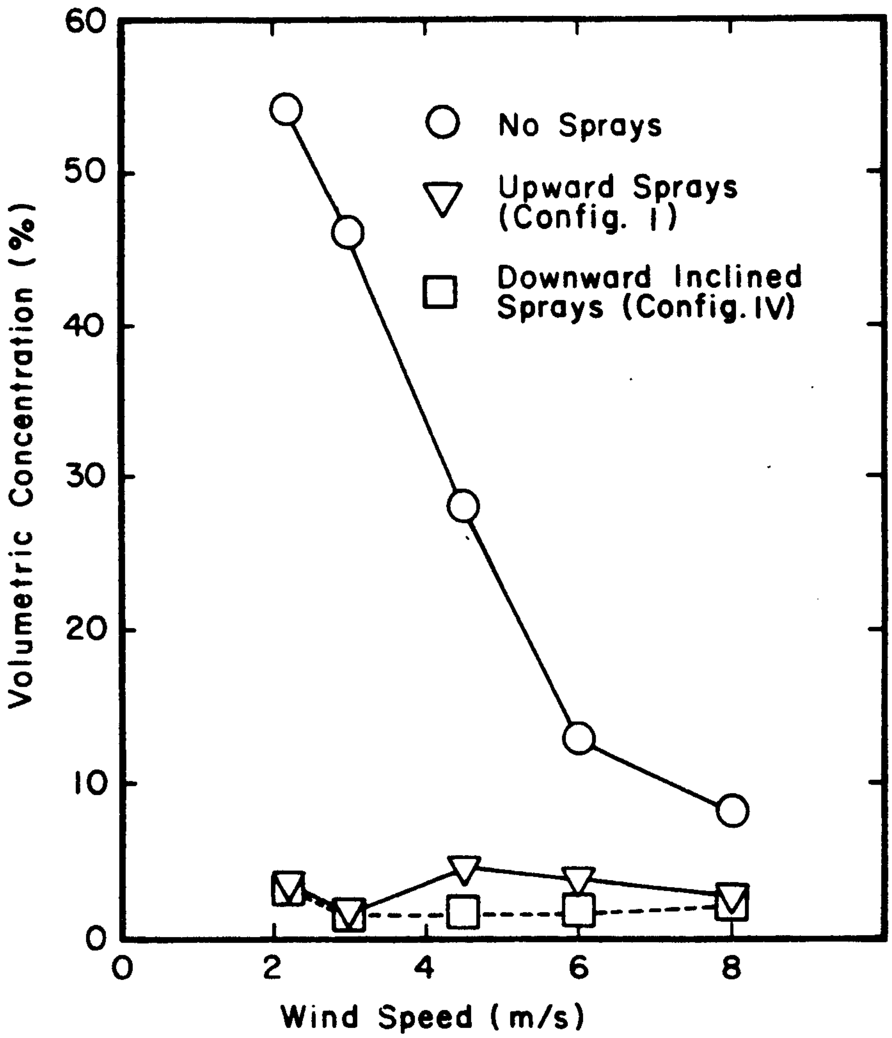

FIGURE 10 INFLUENCE OF SPRAY CURTAINS ON MAXIMUM GROUND LEVEL VAPOR CONCENTRATIONS 60m DOWNWIND OF 60m x 60m DIKE ($\dot{q}''_v$ = 0.029 m/s or $\dot{m}$ = 180 kg/s).

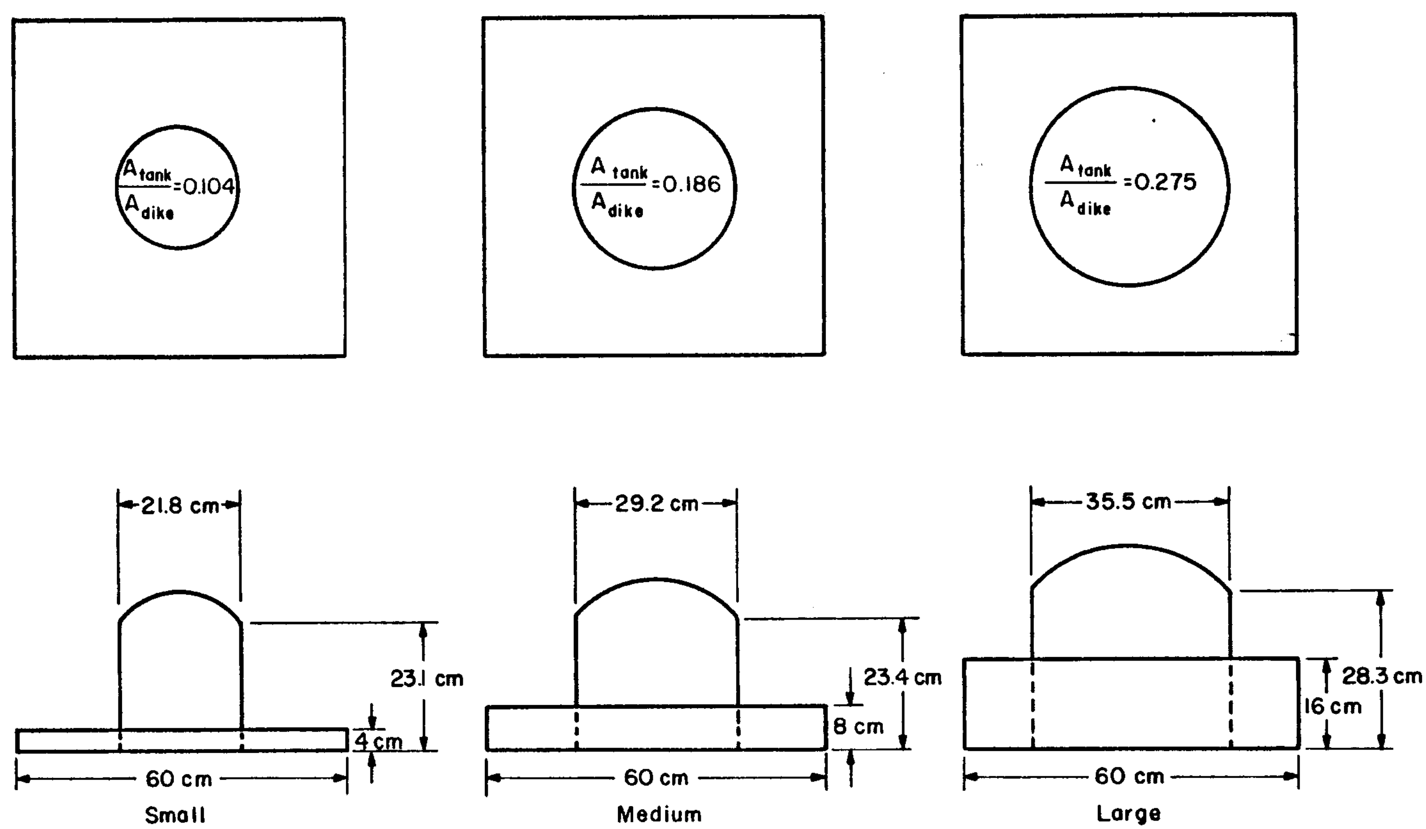

FIGURE 11 STORAGE-TANK/DIKE-HEIGHT COMBINATIONS (MODEL SCALE)

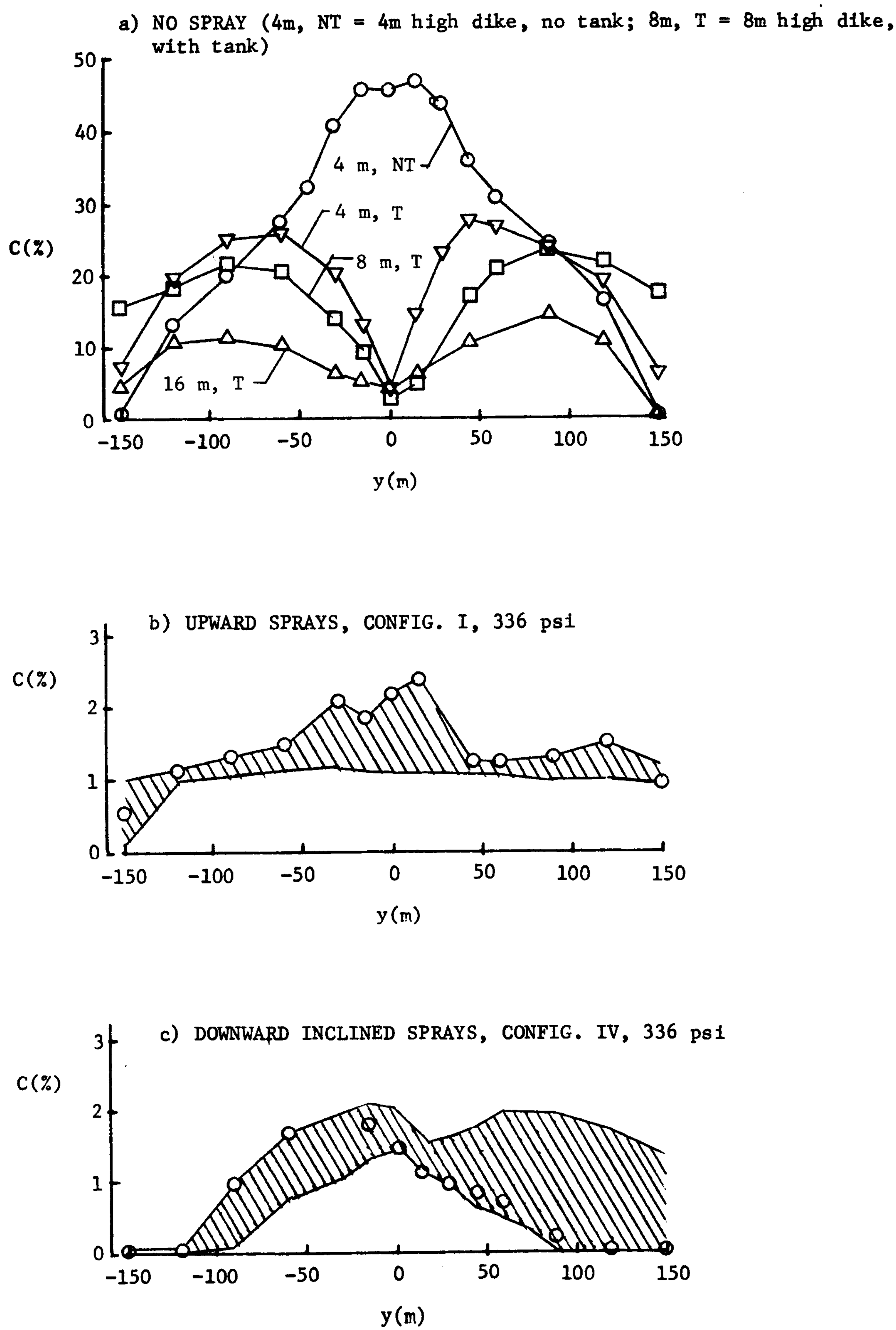

FIGURE 12 CROSSWIND VAPOR CONCENTRATIONS NEAR GROUND LEVEL AT x = 90m FOR VARIOUS COMBINATIONS DIKE HEIGHT/STORAGE TANK (U_w = 3.0 m/s, $\dot{m}$ = 180 kg/s). CIRCLES REPRESENT 4m HIGH DIKE WITHOUT STORAGE TANK. SHADED AREA INDICATES RANGE OF DATA.

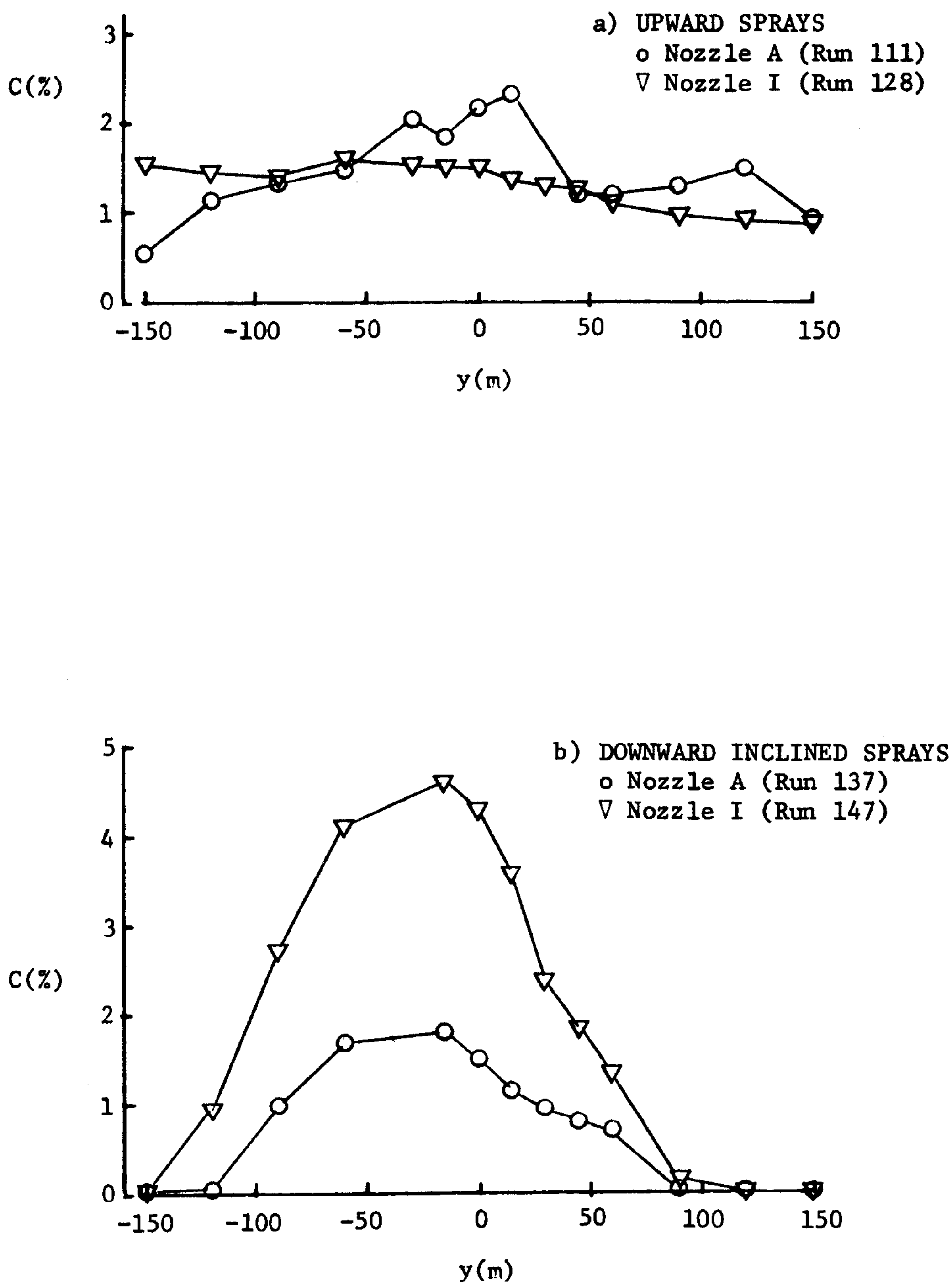

FIGURE 13 NOZZLE A AT 336 psi VERSUS NOZZLE I AT 59 psi; CROSSWIND VAPOR CONCENTRATIONS NEAR GROUND LEVEL AT x = 90m (U_w = 3.0 m/s, $\dot{m}$ = 180 kg/s).