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WIND-TUNNEL SIMULATION OF FIELD DISPERSION TESTS (BY THE U.K. HEALTH AND SAFETY EXECUTIVE) OF WATER-SPRAY CURTAINS

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Abstract. Field trials of water-spray curtain tests performed by the (British) Health and Safety Executive and designated by HSE 41 and HSE 46 were modeled at a scale ratio of 1:28.9 in an atmospheric boundary-layer wind tunnel. The tests confirmed that dense clouds of carbon dioxide gas were significantly diluted by additional air entrained by the water curtain. Linear and logarithmic scatter diagrams of concentrations measured at equivalent scaled points produced correlations of 0.87 and 0.97, respectively. Results confirm the use of Froude-number modeling of both the dense gas cloud and water spray droplet fluid dynamics.

1. Introduction

Water-spray curtains could provide an effective rapid dilution mechanism for low lying dense gas clouds. For example, natural gas is commonly liquified and stored at cryogenic temperatures; hence, a dense gas dispersion situation occurs upon rupture of a storage tank or a spill in a process area. Since for most atmospheric conditions the cold liquified natural gas (LNG) cloud will remain negatively buoyant for significant time intervals, a ground-level hazard may exist due to the gas flammability. Wind-tunnel simulations of scaled situations where water-spray curtains and dense gas clouds interact provide design information for curtain installations and calibration data to validate or develop numerical models. Such a program to determine how well water curtains can mitigate actual spill conditions was completed by Heskestad *et al.* (1983).

Full-scale dispersion experiments with water curtains were sought which could be simulated in the wind tunnel to check the validity of the modeling method. A field series was performed by the Health and Safety Executive, U.K., in 1981 using cold CO_2 vapor (-79 °C) at an estimated spill rate of 1.1 kg sec^{-1} from a point source (Moodie *et al.*, 1981). Two of these tests were selected for simulation in the wind tunnel (at a scale ratio of 1:28.9). Trials HSE 41 and HSE 46 were chosen because of availability of model size nozzles, practicality of scaling ratios, and apparent quality of the data.

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2. Simulation Criteria for Dense Clouds and Water-Spray Motion

To simulate water curtain mutigation of dense cloud hazards adequately, one must duplicate the scaled mixing behavior of the atmospheric boundary layer, the dense gas cloud, and the water spray droplets. During the HSE trials, atmospheric stratification and the earth's rotation were not important over the cloud trajectories studied; hence, partial simulation of the atmospheric boundary layer was appropriate. The tunnel was adjusted to duplicate measured wind speed profiles, surface drag coefficient, and scaled surface roughness. The gas cloud's motion was governed by inertial and gravity forces; hence, simulation of an equal cloud-source Froude number, source specific gravity, and volume flux ratio was appropriate. Movements of water droplets released from a spray nozzle are also governed by inertial and gravity forces; hence, equality of water-spray Froude number and volume flux is necessary. Summarizing, equality of the following criteria were considered appropriate for a simulation of dense gas cloud dispersion by water-spray curtains:

u_*/u_R	Surface drag coefficient
z_0/L	Surface roughness coefficient
$u_R^2/[g(SG_0 - 1)L]$	Dense-cloud Froude number
SG_0	Source specific gravity
$Q/(u_R L^2)$	Volume flux ratio of gas cloud
$u_R^3 L/(gQ_s)$	Water-spray flux Froude number
D/L	Diameter of water-nozzle scale ratio
$\Delta p_s/\rho u_R^2$	Nozzle pressure coefficient

provided that the mass mean droplet size scaled as the square root of the linear scale ratio, and where Q and Q_s are the volume fluxes of dense gas and the water, respectively. For an amplified discussion of shear layer and dense-gas similitude, see Neff and Meroney (1983) or Meroney *et al.* (1978). Spray-nozzle physics is discussed by Heskestad *et al.* (1983).

3. Experimental Configuration

The HSE field trials 41 and 46 were modeled at the scale ratio of 1 : 28.9 in the wind tunnel at Colorado State University. This atmospheric boundary-layer wind tunnel has a test section 3.66 m wide, 2.28 m tall, and 17.0 m long. Vortex generators and a wall trip at the test section entrance produced a boundary layer about 1 m deep at the experiment location, 9.2 m downwind of the entrance.

A miniature source (Figure 1) was constructed to reproduce the radial exhaust characteristics of the source used by the HSE researchers. Sampling points were located at equivalent field locations. In addition, a full crosswind ground-level sampling profile was made just downwind of the HSE field sampler array. During HSE Trial 41, four model nozzles were located 10.4 cm above the floor, spaced 11.75 cm apart and pointed 45° forward of vertical and downward just as in the field situation. During HSE Trial 46, the model spray curtain consisted of 20 nozzles discharging at a 10.4 cm height, spaced 5.66 cm apart, and directed vertically downward.

The source gas used in all runs to simulate the cold CO_2 was a mixture of 68% CO_2, 31% CCl_2Fl_2, and 1% C_2H_6 (used as a tracer); thus it had the proper specific gravity value (i.e., 2.35) of the cold CO_2 field plume. Concentrations were measured with a flame-ionization detector in a gas chromatograph. Samples were taken from the wind tunnel with a sampling system consisting of fifty 30 cc syringes which simultaneously drew samples at a rate of 6 cc min^{-1} over a 5-min averaging period. The system could measure concentrations to less than 0.1% with an accuracy of $\pm 5\%$.

The velocity profile, reference wind speed conditions, and turbulence levels were measured with a hot-film anemometer system. The accuracy of the results are approximately $\pm$ 20% or $\pm$ 5.0 cm sec^{-1}, whichever is smaller. Gas flow rates were monitored with a low-volume flowrator; water pressures were set with a calibrated Bourdon-tube pressure gauge.

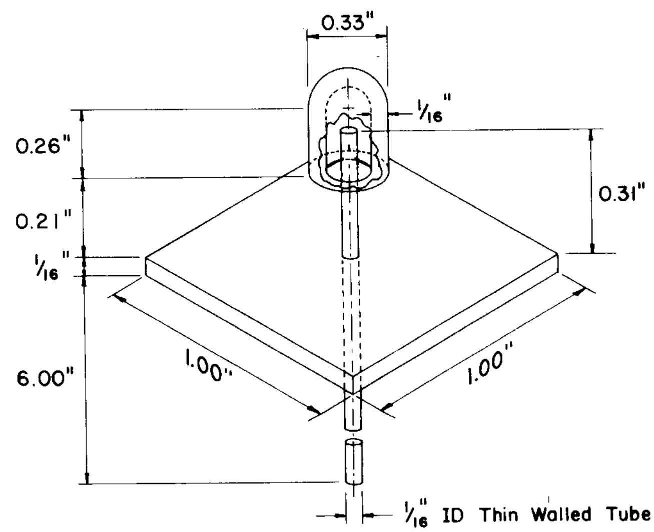

Fig. 1. Model of HSE source for wind-tunnel studies.

4. Model Test Results

Source gas flow rates, wind speeds, and water pressures during the field and model trials were varied as shown in Table I. Downwind water curtain placement, sampler location, and wind orientation for the two tests are noted on Figures 2 and 3. The wind-tunnel flow field reproduced field conditions accurately as noted from the comparison of velocity profiles in Figure 4.

TABLE I

Model test conditions during HSE Trials 41 and 46

HSE Trial	Source flow rate[a] (kg sec^{-1})	Wind speed[b] (m sec^{-1})	Wind direction (°)	No nozzles[c]	Spray pressure gas (kPa)	Model source flow rate (ccs)	Model wind speed[d] (cm sec^{-1})	Wind direction (°)	No. of nozzles[e]	Water pressure (kPa)
41	~1.1	3.2 ± 0.5	352 ± 10°	–	–	87	63	352	–	–
41	~1.1	3.2 ± 0.5	352 ± 10°	–	–	87	63	345	–	–
41	~1.1	3.2 ± 0.5	352 ± 10°	4	400	87	63	345	4	31
46	~1.1	2.9	323 ± 5°	–	–	87	55	323	–	–
46	~1.1	1.7	323 ± 5°	–	–	87	32	316	–	–
46	~1.1	1.7	323 ± 5°	20	700	87	32	316	20	46

[a] Corrected for a portion of CO_2 which falls out solid as dry ice.

[b] At 1.25 m.

[c] Field spray nozzles were a Model 2H60 for Trial 41 and an Angus Fyrhed 14 mm for Trial 46.

[d] At 4.33 cm.

[e] Model spray nozzles were a special nozzle manufactured by Sprayco, Inc. for FMRC with nozzle diameter 0.99 m and angle of 62° for Runs 41 and Model 19577604 manufactured by Sprayco, Inc. with nozzle diameter 0.46 mm and angle of 38° for Runs 46.

$l_b = \frac{Q g'}{u^3} = 0.4 \quad f: \; Q^{1/2} g' / U^{5/2} = 0.822$

$L_{U_0} = 18.2 (l_b / f^{0.8}) =$

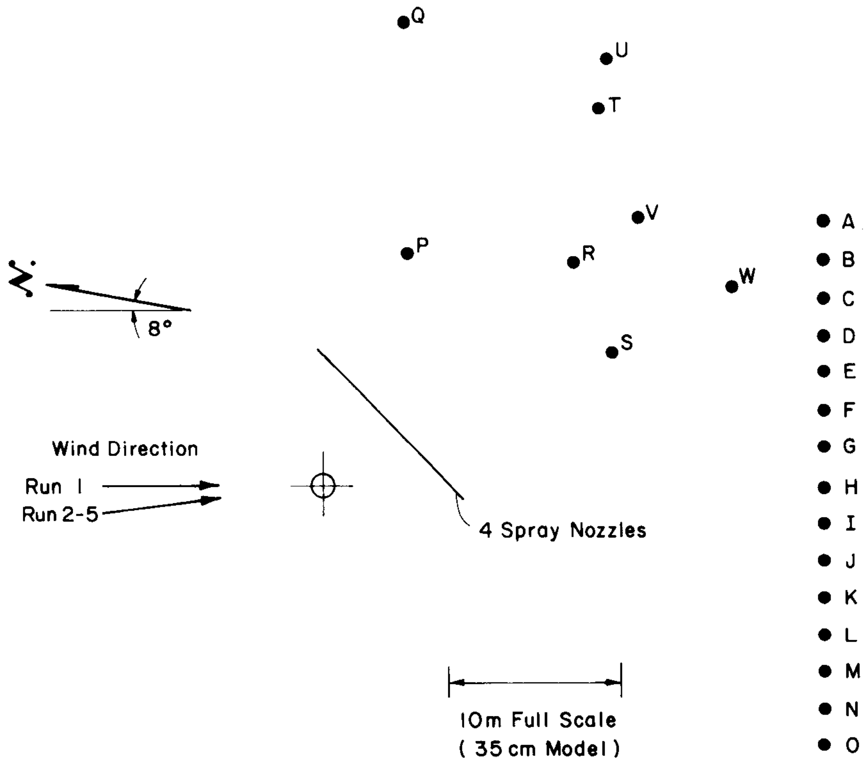

Fig. 2. Plan view of HSE run number 41.

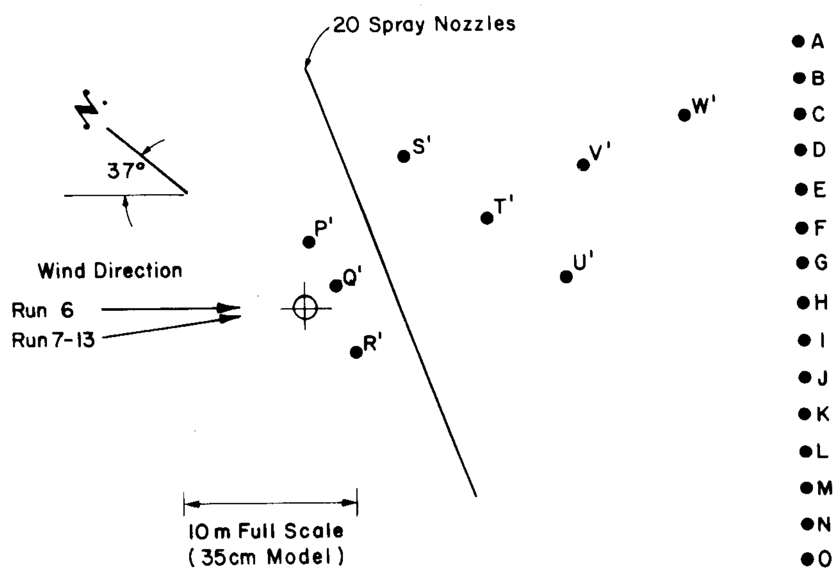

Fig. 3. Plan view of HSE run number 46.

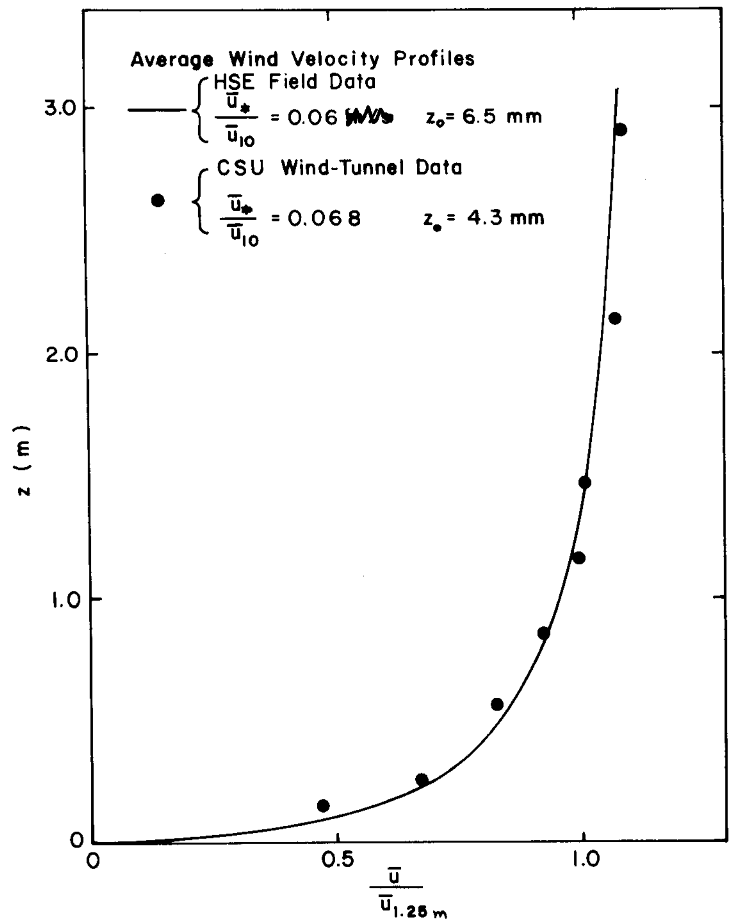

Fig. 4. Average wind velocity profile comparison between HSE field and CSU model data.

4.1. HSE Trial 41

The average field wind speed recorded for HSE 41 was about 3.2 m sec^{-1} for the no-spray and spray intervals (Figure 5). The wind field appeared very turbulent, and the wind speed varied by $\pm$ 0.5 m sec^{-1} during test intervals. In addition, the wind shifted up to 20° during the no-spray measurement period and 40° during the active spray period. It was not possible to produce a plume which spread up to +80° around the source as seen during the field test with any model source perturbation examined. Field concentrations were measured at stations as far laterally as point Q (T32 field) in Figure 2. This seems extremely puzzling since the buoyancy length scale, ratio $l_b/L = Qg'/(u^3L)$, was rather small, and previous measurements (Neff and Meroney, 1981) for continuous and finite time releases from area sources always produced narrow plumes under equivalent l_b ratio conditions. Indeed, such narrow shaped plumes were detected during the model tests. During spray conditions, the plume was deflected to

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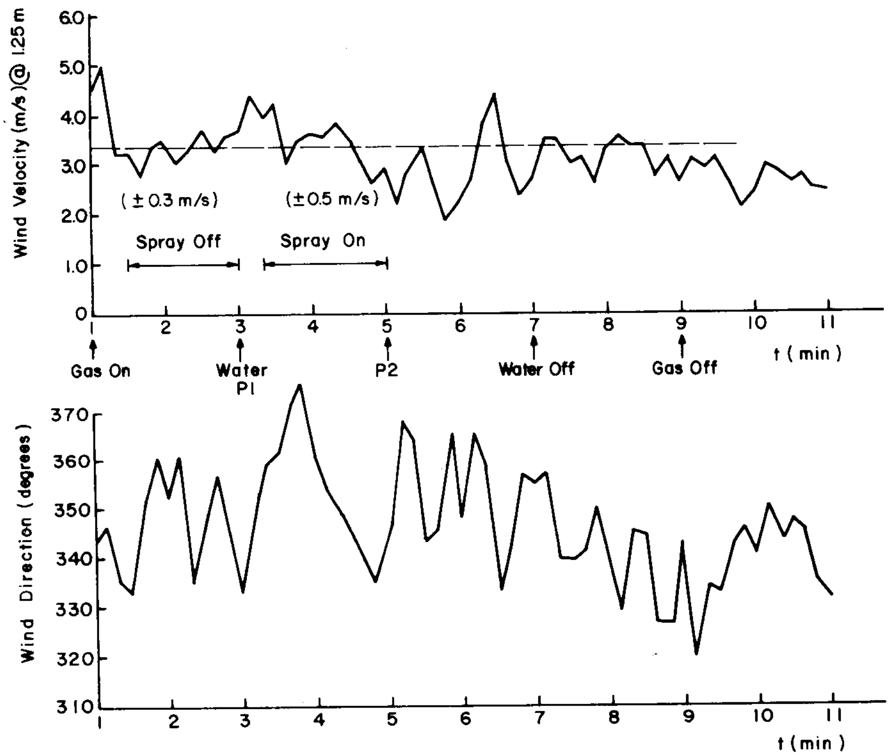

Fig. 5. Wind direction and wind velocity field data for HSE run number 41.

the west and concentrations were significantly reduced. Correlation between field and laboratory measurements were near zero. Nonetheless, the peculiar breadth of the field plumes suggests that this is influenced by additional field features such as source icing, upwind storage tanks, wind meandering, etc. not included during the model simulation. A simple mass balance performed over field measurement stations for HSE 41 failed to agree with the estimated source strength provided for the run.

Subsequent communication with HSE personnel indicated that during later tests when simultaneous wind measurements were made at two locations, but at the same height, significant unexplained differences in the velocity readings between otherwise similar locations occurred. It is very likely that the wind instrument used by HSE was in the wake of other test equipment during this test; thus the model data for any Trial 41 tests are inconclusive.

4.2. HSE Trial 46

In the field, the wind speeds at 1.25 m for HSE 46 were reported to average 2.9 m sec^{-1} during an initial no-spray interval (0–3 min), and 1.7 m sec^{-1} during the subsequent (3–5 min) spray interval (Figure 6). Using an equivalent scaled velocity corresponding to 2.9 m sec^{-1}, the wind-tunnel results did not reproduce the field conditions, the lateral spread of the field vapor plume being greater. Based on the large errors found in the

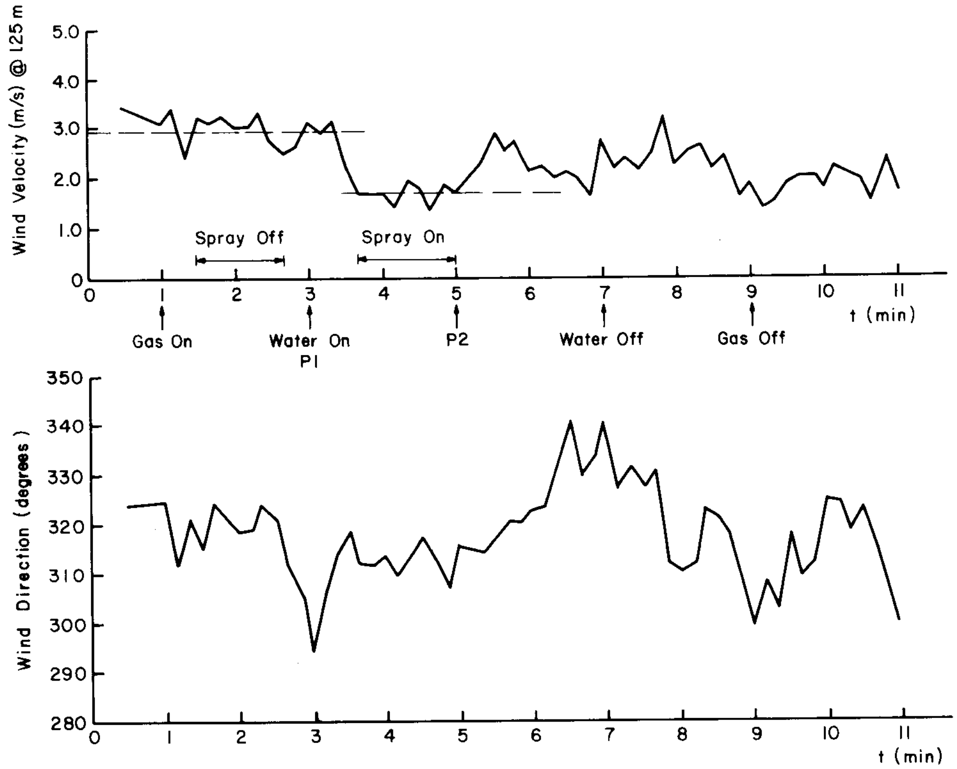

Fig. 6. Wind direction and wind velocity field data for HSE run number 46.

velocity data during HSE 41, the wind spread was reduced to a level where the plume behaved as observed during the field experiment. When the wind speed was reduced to the equivalent of 1.7 m $\sec^{-1}$, the model data reproduced the no-spray conditions quite well. Linear and logarithmic scatter diagrams of concentrations measured at equivalent scaled points produce correlations, r, of 0.87 and 0.97, respectively (Figure 7). Figures 8 and 9 show comparisons between the horizontal and vertical values of field and model concentrations. The vertical plots in particular reveal similar magnitudes of concentration and cloud depths. Without the mixing of the spray curtain, the gases are spread in a shallow but wide 'pancake' cloud.

During the active water-spray period for HSE 46, model concentrations agreed well with field measurements (see Figure 7). Figures 10 and 11 display horizontal and vertical concentration variations during the spray portion of HSE 46. Maximum concentrations are reduced by factors from four to six. Additional vertical entrainment more than triples the depth of the cloud.

Table II compares field and model conditions by means of the forced diffusion ratio, FD, suggested by Moore and Rees (1981) where

$$FD = \frac{(u_{1.25})_{\text{no spray}}}{(u_{1.25})_{\text{spray}}}$$

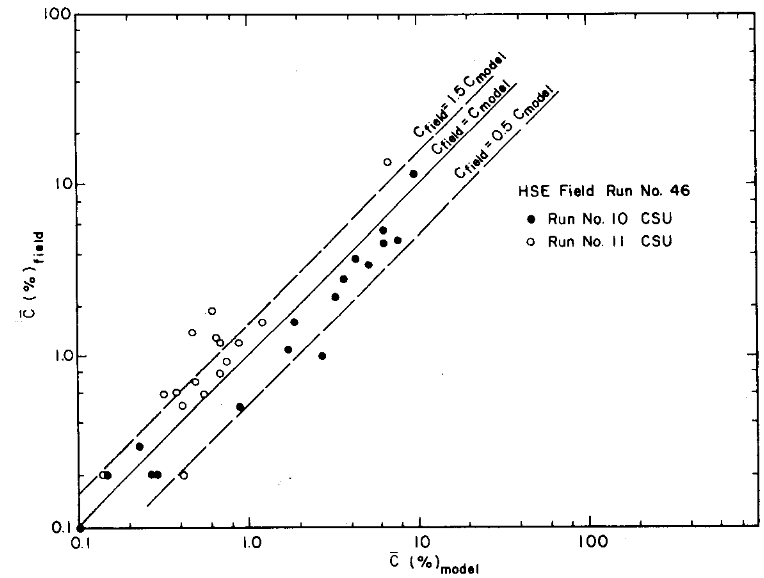

Fig. 7. Logarithmic scatter diagram comparing HSE field and model concentrations, HSE run number 46.

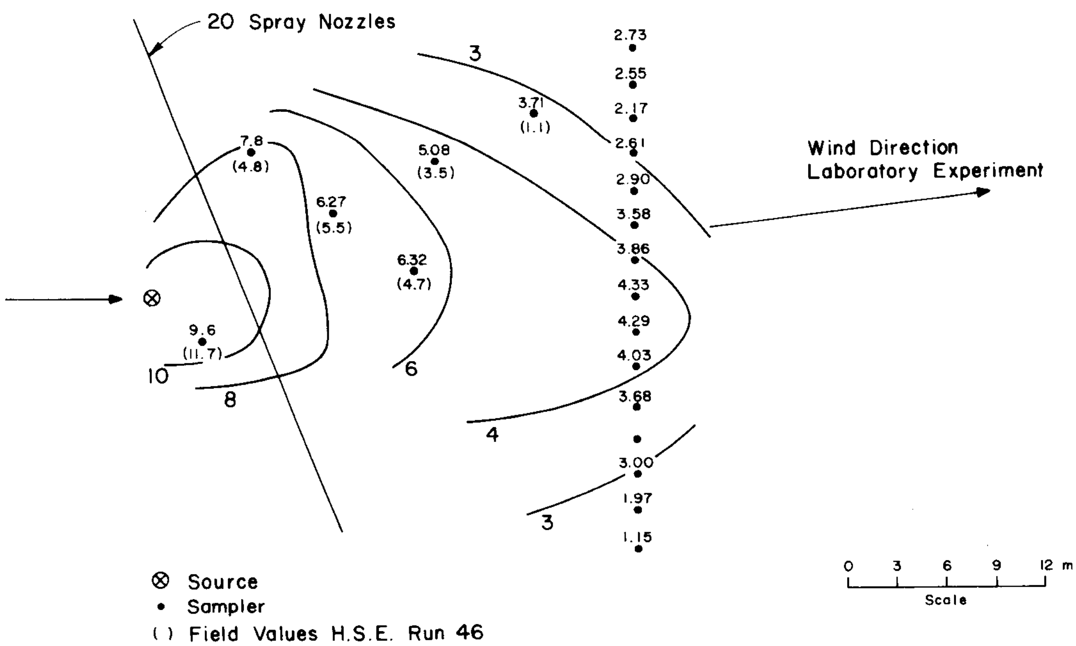

Fig. 8. No-spray ground-level concentration isopleths for HSE run number 46.

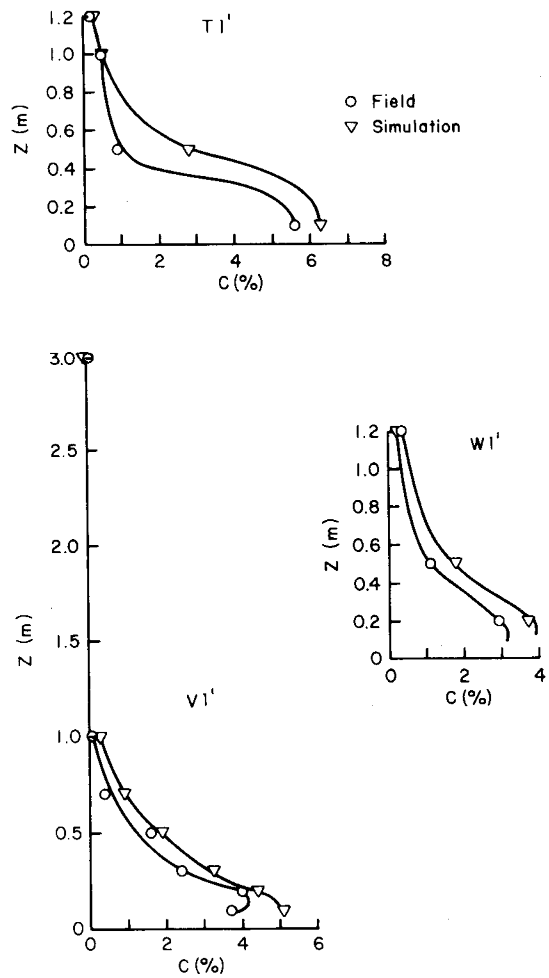

Fig. 9. No-spray vertical concentration profiles, HSE run number 46.

and a Per cent Dilution Ratio, i.e.,

$$\%\ \mathrm{Dil} = 100\left(\frac{C_{\text{no spray}} - C_{\text{spray}}}{C_{\text{spray}}}\right).$$

Between the wind-tunnel and field measurements, there is a linear correlation, r, of 0.78 and 0.71 for FD and % Dilution, respectively. The scaled no-spray conditions tended to overpredict field values, whereas the scaled spray values tended to underpredict field values slightly. Considering the uncertainties associated with the HSE tests, the laboratory models provided a very credible simulation of the water-spray curtain's ability to dilute dense clouds.

TABLE II

Forced dispersion factors and recent dilution during water-spray tests for HSE Trial 46

Field position	C % field w/o spray	C % field w spray	Field		Wind tunnel	
			FC	% Dil	FD	% Dil
T19[a]	11.7	13.8	1.45	−18	1.41	29
T05	4.8	1.9	4.31	53	12.38	92
T08	5.5	1.2	7.82	78	6.82	85
T11	1.0	0.8	2.13	20	3.97	75
T33	0.6	1.4	0.73	−133	1.10	9
T14	0.2	0.5	0.68	−150	0.66	−52
T17	4.7	1.6	5.01	66	5.18	81
T04	3.5	0.9	6.63	74	6.86	85
T06	3.8	1.2	5.40	68	6.24	84
T03	2.3	0.7	5.61	70	6.56	85
T21	1.6	0.6	4.55	63	3.41	71
T18	0.5	0.5	1.71	0	–	–
T27	0.2	0.2	1.71	0	0.69	−45
T23	0.0	0.2	0.00	−∞	0	−∞
T37	2.9	1.3	3.81	55	5.54	82
T28	1.1	0.6	3.13	45	3.26	69
T32	0.3	0.6	0.85	−100	0.59	−70
T31	0.2	0.6	0.57	−200	0.47	−113

* $FD = \dfrac{C_{w/o\ spray} u_{ws}}{C_{w\ spray} u_{w/o\ s}}$ defined by Moore and Rees (1981) $u_{Field\ w/o\ spray} = 2.9$ m sec^{-1}

$u_{Field\ w\ spray} = 1.7$ m sec^{-1}

$$\%\ \text{Dilution} = \frac{C_{w/o\ spray} - C_{w\ spray}}{C_{w\ spray}} \times 100$$

r^2 (Field/10–11)$_{FD}$ = 0.61, $r = 0.78$

r^2 (Field/10–11)$_{\%\ D}$ = 0.50, $r = 0.71$

[a] A post check on apparatus suggests model measurements at T19 may have been in error and 50% low.

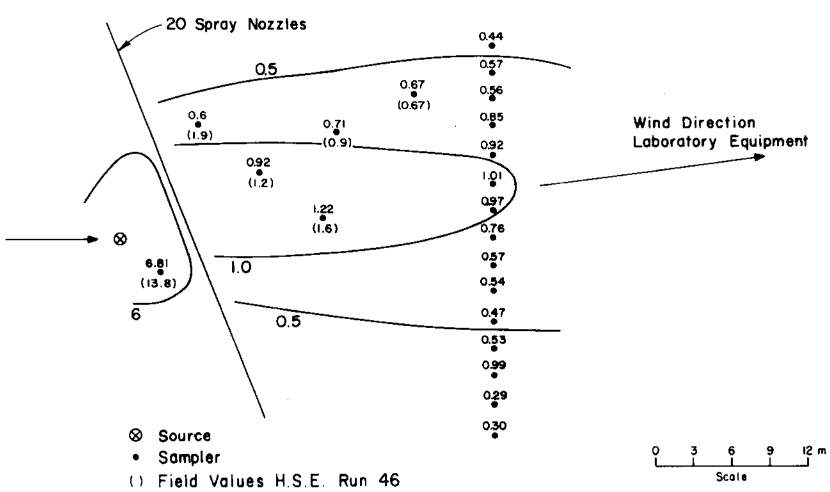

Fig. 10. Active spray ground-level concentration isopleths for HSE run number 46.

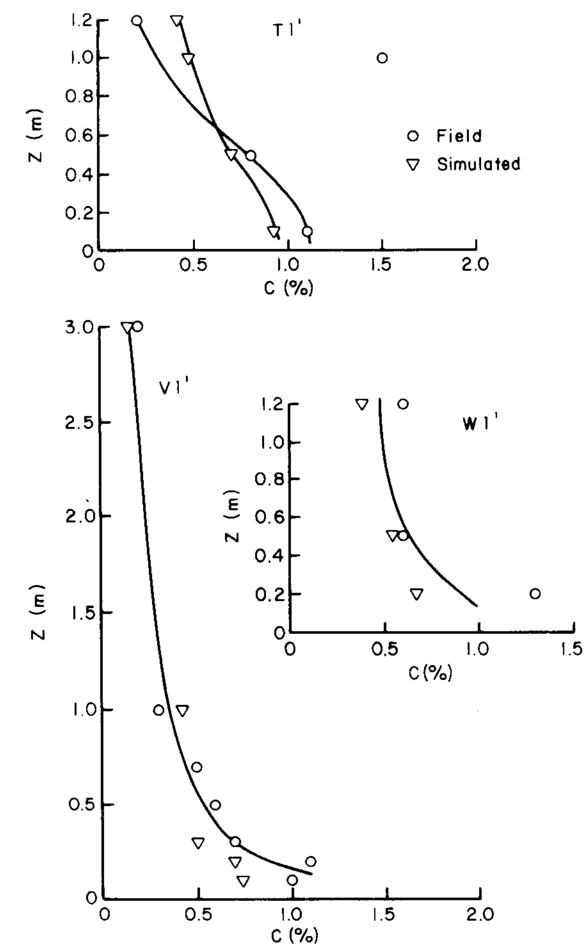

Fig. 11. Active spray vertical concentration profiles, HSE run number 46.

5. Conclusions

Because of the possible errors in field wind speed, the physical modeling exercise cannot be considered absolutely conclusive. Nonetheless, HSE Trial 46 was satisfactorily replicated in the wind tunnel. In addition, the tests demonstrated the ability of physical modeling to evaluate the advantages of different source and spray curtain configurations without the confusion caused by the nonstationary atmosphere. This could be done quickly and cheaply.