A Comparison of Diffusion from a Small Island and an Undisturbed Ocean Site[1]

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ABSTRACT

Experiments were conducted to investigate the differences in diffusion from an obstacle to free air flow in the ocean and from an undisturbed ocean site. A small island was used as the obstacle and simultaneous releases of oil-fog smoke were made from the island and from a nearby boat. The widths of the plumes and their concentration distributions were measured quantitatively during traverses across the plumes by a second boat. Extensive series of photographs were taken of the plumes from the surface and from the air. Meteorological measurements were made at two locations on the island, from the boats and from an aircraft. One test series was conducted during unstable conditions and a second series with neutral and stable conditions.

Width of the island plume over short periods was from 1.5 to 4 times that of the boat plume with the greatest difference during stable periods. Over longer periods, the differences were somewhat greater and much of the dispersion was caused by plume meander. Height of the island plume averaged about twice that of the boat plume. Normalized maximum centerline concentrations from the boat plume were 1.4 times those of the island plume during unstable periods but about twice during stable and neutral conditions. Averaged over all tests, dispersion from the island was about twice as great as from the boat.

1. Introduction

A previous paper (Raynor *et al.*, 1975) described preliminary results from studies of atmospheric diffusion from a nearshore oceanic site. These studies were initiated to help evaluate potential environmental impacts from nuclear power plants or other installations sited in offshore locations. They provided unique data on diffusion over the water from a point source and its relationship to meteorological variables. Earlier studies of coastal meteorology and diffusion were summarized by Prophet (1961) and Van der Hoven (1967). Other pertinent literature was discussed in our earlier paper (Raynor *et al.*, 1975).

In an actual situation, diffusion from a structure as large as a power plant would be modified by the disturbed airflow around the building. The purpose of the experiments reported here was to investigate the differences in diffusion rate between a plume from an obstacle to free air flow over the ocean and a simultaneous plume from an undisturbed oceanic site. Such information is essential to realistically predict diffusion rate and the resulting environmental impact of any airborne release from an offshore structure, but this information is not available from previous studies.

Several field experiments on the effect of large land-based structures on diffusion have been conducted (Davies and Moore, 1964; Islitzer, 1965; Hinds, 1967; Culkowski, 1967; Dickson *et al.*, 1967; Munn and Cole, 1967; and Abbey, 1976), but results are not readily applicable to the overwater situation. Barry (1964) evaluated a number of the empirical formulae proposed to that date and Abbey (1976) summarized many of the previous studies.

The numerous wind tunnel tests of airflow and diffusion around model buildings have provided a fundamental understanding of the problem, but these studies have been restricted to simplified conditions seldom existing in the outside atmosphere. Among such studies, those by Halitsky (1968), Meroney (1971), Hansen *et al.* (1974) and Huber and Snyder (1976) are representative. Meroney *et al.* (1974) investigated the behavior of airborne materials released from a floating nuclear power plant under neutral and stable conditions, but only with respect to concentrations around the building itself. Meroney and Cermak (1967) modeled flow and diffusion over San Nicolas Island, Calif., and compared results with available field data.

In the absence of definitive guidelines, various procedures have been used to estimate initial dilution and plume spread caused by large structures. In one Generic Environmental Report (Off-shore Power Systems, 1973) an initial value for plume height (σ_z) equal to one half the height of the structure was used in diffusion calculations. Previous authors have modified stan-

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dard diffusion equations by a building wake constant and a term for the cross sectional area of the building (Barry, 1964; Islitzer, 1965; Yanskey *et al.*, 1966; Slade, 1968; and Sagendorf, 1974), but the optimum magnitude of the constant and the applicability of this technique to offshore structures have not been demonstrated.

2. Site

In the absence of an actual ocean-based structure from which to conduct experiments, a small island was selected as the best available substitute. Great Gull Island is located at 41°12′N, 72°07′W, about 10 km northeast of Orient Point, the northeasternmost portion of Long Island. The nearest land is Plum Island, a larger island 3.5 km to the WSW. Land areas in other directions are 8 to 20 km distant. Thus, a good fetch over the ocean exists in all directions.

The island is about 800 m long, 175 m across at its widest point and tapered at both ends. It is hilly and rocky and contains numerous remnants of concrete fortifications and rock walls built prior to the Spanish-American War by the U. S. Army for coastal defense purposes. Maximum ground elevation is about 12 m and the tallest structure remaining is about 18 m above the water. The island has no electric power, telephone or water supply. It is owned by the American Museum of Natural History and is used primarily as an ornithological research station. Thus, our experiments could be conducted only outside of the summer season.

3. Methods

a. Research plan

The basic plan of the experiments was the simultaneous release of a visible tracer (oil-fog smoke) from the island and from a small boat (LCM-8) anchored in a nearby position undisturbed by flow over the island (Fig. 1). The center, upwind side and downwind side of the island were each used as release points in several tests. The width of the plumes and their concentration distribution at one or more distances downwind were measured by an instrument mounted in a second boat. Extensive series of photographs were taken from the island, from the second boat and from an aircraft to further document the appearance and behavior of the plumes. Concurrent meteorological measurements were taken from two locations on the island, from the boats and from the aircraft. One series of experiments was made in September 1974 when water temperature was near its maximum for the year and low-level lapse rates over the ocean were mostly unstable. A second series was made in late April and early May 1975 to sample more stable conditions since the ocean was still cold and the air generally warmer.

b. Meteorological instrumentation

A 10 m mast was mounted on the western tip of the island close to the water's edge and just above high tide level. This location had an unobstructed fetch over the water in all directions except ENE and no experiments were conducted with that wind direction. Thus, measurements taken here are representative of conditions over the ocean. In both years, sensitive cup anemometers were mounted at six levels and aspirated thermocouples at four. A sensitive bivane (Meteorology Research, Inc.) and a fast response humidity sensor (Thunder Scientific) were mounted at 10 m. In 1975, a temperature fluctuation probe (Thermosystems) was used at the same level. Power was supplied by a gasoline powered electrical generator. Counters, chart recorders and magnetic tape recorders were used to record the data and were housed in a nearby tent.

A 6 m mast was placed on the roof of a small concrete building near the center of the island to sample conditions over the land. Cup anemometers were mounted at four levels and a sensitive bivane (Climet) at 6 m. A thermistor temperature sensor was mounted at 6 m in 1974 and a hot wire anemometer at 2 m in 1975. Power was supplied here also by a generator while recorders were housed in the building below the mast.

Pilot balloon ascents were made periodically from this location. Kytoon-mounted temperature sensors were used both here and from the LCM to obtain temperature profiles below aircraft flight level. Air and water temperatures were taken from both boats with mercury thermometers.

A chartered Cessna-172 single-engine aircraft was equipped with temperature and turbulence instrumentation and an infrared thermometer (Barnes PRT-5) for measurement of surface temperature. The infrared measurements of water temperature agreed well with those taken from the boat. The instruments were described in more detail previously (Raynor *et al.*, 1975).

c. Tracer instrumentation

Oil-fog smoke was produced by one Model 400B Dyna Fog smoke generator mounted on the LCM and another on the island. Output was monitored periodically. Smoke from the boat was emitted 8.1 m above the water through a stack. Smoke from the island was released near ground level at locations selected on the basis of wind direction and the needs of the experiment. Oil-fog smoke has a mean droplet diameter of 0.6 μm and behaves as an aerosol in the atmosphere. Deposition to either land or water surfaces has not been measured but is believed minimal because of the small droplet size.

Concentrations were measured by a photometric densitometer (Brown *et al.*, 1972) mounted on the second boat. Multiple traverses were made across both plumes at fixed speed using marker buoys previously anchored as end points of the traverses. Positions of the LCM and the marker buoys were determined by triangulation from two locations on the island. In each

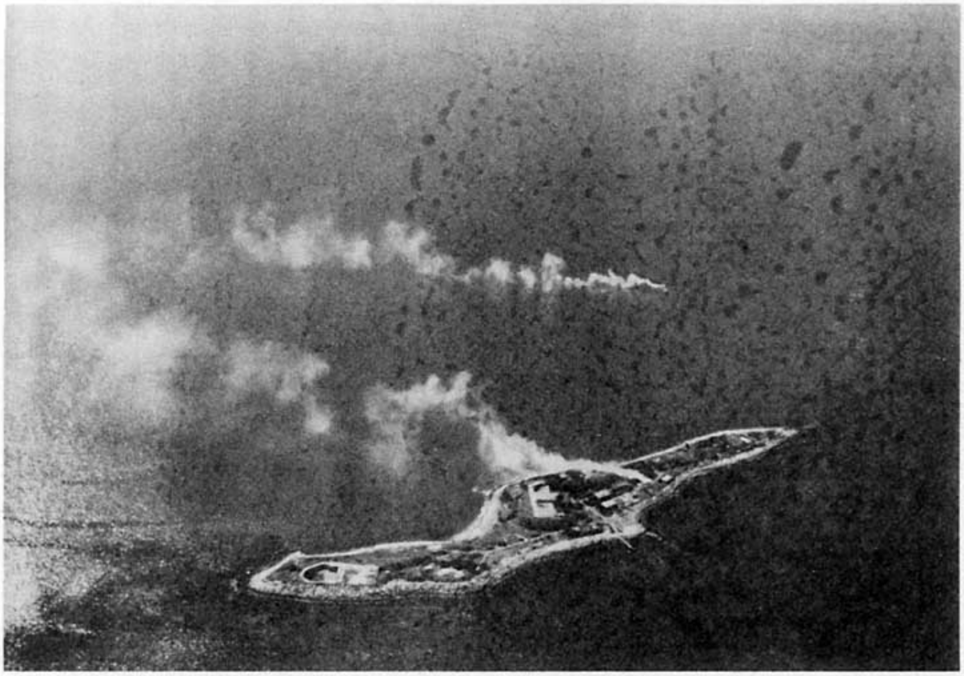

FIG. 1. Aerial view of Great Gull Island showing smoke plumes from the island and the boat.

test, sets of traverses were made at one or more distances.

d. Procedures

Before each experimental period, equipment was taken to the island and placed in position. On days selected for experiments, personnel were transported to the island by boat and instruments were mounted on the masts. The smoke generator was moved to the selected release position. On most days, separate tests were conducted in the morning and afternoon, sometimes with different release positions or with different wind directions but on some days, only one test was obtained. Activities of personnel on the boats, the aircraft and the island stations were coordinated by radio.

TABLE 1. Description of run conditions.

Test no.	Date	Time (EST)		Source location Island	Boat	Wind direction	10 m wind speed (m s^{-1})	Weather	Ri_4	Plume behavior
1	23 Sep 74	1203	1415	Center	NW	NW	7.92	⦶ Cu	−0.58	Unstable
2	24 Sep 74	1045	1255	Center	W	NE	5.61	○—⦶ Cu	−0.94	Unstable
3	24 Sep 74	1255	1352	Center	W	Var.	2.40	⦶ Cu	−0.94	Unstable
4	25 Sep 74	1000	1129	Downwind	SW	SE	8.33	⦷ Ci, Cu	−0.01	Unstable
5	25 Sep 74	1216	1355	Downwind	SW	SE	7.88	⦷ Ci, Ac, Sc	−0.01	Unstable
6	26 Sep 74	0953	1213	Upwind	SW	NW–W	3.43	⦶ Ci– ⦷ Ci, Cu	−0.32	Unstable
7	26 Sep 74	1308	1423	Upwind	SW	NW–W	5.10	⦷ Ci Ac—⊕ Cs, Ac, As	−0.32	Unstable
8	27 Sep 74	1102	1435	Downwind	N	WSW	4.20	○, H+	+0.05	Near neutral
9	21 Apr 75	1215	1415	Center	WSW	NW	11.26	⦷ Cu, Sc	+0.17	Slightly unstable
10	22 Apr 75	1000	1120	Center	S	WSW	4.76	⦶ Ci	−0.06	Near neutral
11	22 Apr 75	1225	1410	Center	SE	SW	6.67	⦶ Ci	+0.03	Near stable
12	23 Apr 75	1025	1324	Center	SW	S	2.24	○, H	+0.82	Stable
13	23 Apr 75	1324	1442	Center	SW	S	5.63	○, H	+0.17	Near stable
14	28 Apr 75	0955	1043	Downwind	SW	W–WSW	6.65	○	+0.01	Slightly unstable
15	28 Apr 75	1112	1226	Downwind	S	W–WSW	6.81	○	+0.04	Near neutral
16	28 Apr 75	1424	1516	Downwind	S	W–WSW	5.48	○	+0.04	Near neutral
17	1 May 75	0950	1315	Downwind	SSW	SE	5.17	⊕ Ci Cs—⊕ As, Ac	+0.01	Near stable
18	1 May 75	1315	1410	—	S	SE	6.42	⊕ As Ac	+0.01	Near stable
19	3 May 75	1120	1315	Downwind	WSW	SW	2.40	F−, H	+0.50	Near stable
20	3 May 75	1415	1436	—	SW	SW	2.78	H	+0.13	Near stable
21	3 May 75	1545	1604	—	S	SSW	5.10	H	+0.23	Near stable

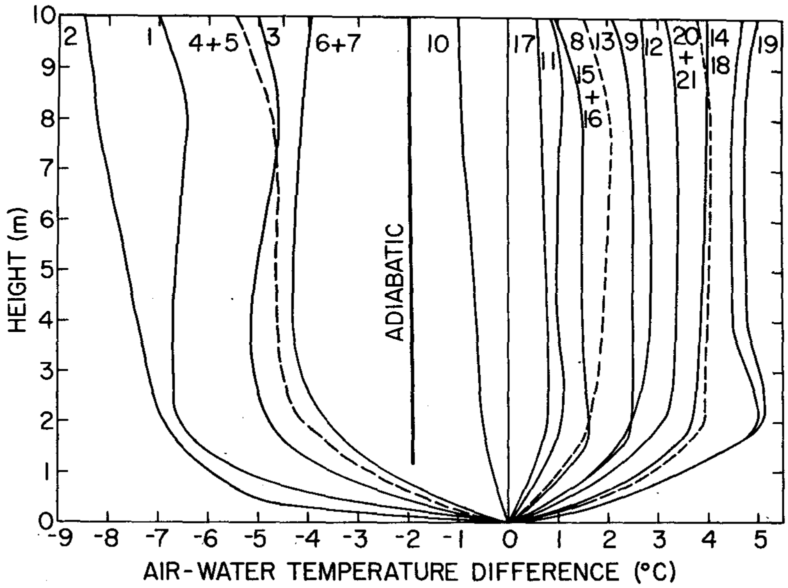

FIG. 2. Temperature lapse rates to a height of 10 m.

Other experimental procedures and analytical methods were similar to those used in previous experiments (Raynor *et al.*, 1975).

4. Results

a. Description of tests

A list of tests obtained is given in Table 1 with source locations, meteorological conditions and observed plume behavior. Wind speeds are means for the duration of the test. Bulk Richardson numbers were computed from measurements on the 10 m tower and are representative of flow over the water. All tests included dual emissions except 18, 20, and 21 in which only the plume from the boat was released and allowed to cross the island.

b. Temperature structure

Tests were conducted over a wide range of lapse rates. Temperature profiles to a height of 10 m are shown in Fig. 2 and to a height of 900 m in Fig. 3. Air temperatures are plotted as deviations from the water temperature which varied only slightly with distance and direction from the island. Profiles are labeled with the number of the run during which they occurred. In both presentations, cases divided into the same two groups, unstable on the left and stable, in the lower

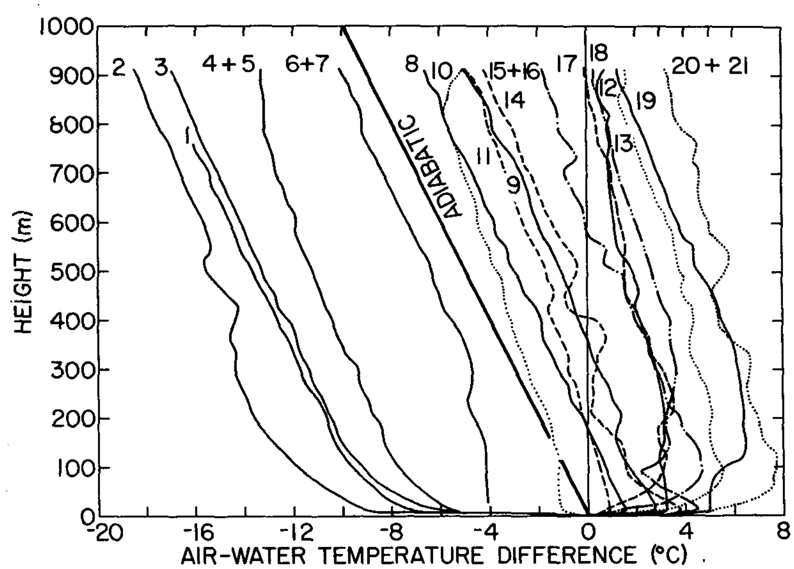

FIG. 3. Temperature lapse rates to a height of 900 m from aircraft measurements.

layers, on the right. The unstable cases are generally characterized by superadiabatic layers near the surface and the stable cases by one or more low-level inversions. The unstable cases were generally observed in the fall series of tests and the stable cases in the spring.

Temperature was measured at only one level at the center of the island but readings were typically well above water temperature giving unstable lapse rates at low levels over land. Early on two mornings in September, the IR measurements showed the island to be colder than the water but land temperatures exceeded water temperatures before tests began.

c. *Wind profiles*

Wind profiles measured at the west end were used to compute roughness lengths, friction velocities and drag coefficients over the water and, with the temperature measured at the same location, to compute bulk Richardson's numbers (Table 1). Roughness lengths were similar to those found over the ocean off the south shore of Long Island (Raynor *et al.*, 1975; SethuRaman and Raynor, 1975). Friction velocities and drag coefficients were also similar. Measurements taken at the center of the island could not be used to compute these parameters over land since the flow was badly disturbed by the structure on which the mast was mounted.

d. *Turbulence*

Turbulence parameters were computed from bivane and hot wire anemometer measurements taken on the two masts (Table 2). Values of $\bar{u}$ given here are for the duration of the turbulence measurements and differ somewhat from those of Table 1. Values of σ_θ, σ_ϕ, σ_u, σ_v, σ_w and $\sigma_u/\bar{u}$ were all appreciably larger over the island, even during periods of instability over the water. This is attributed to the much greater roughness and differential surface heating of the island.

e. *Plume width*

The standard deviation of the crosswind distribution of material in the plume (σ_y) was selected as a measure of plume width and three distinct measures of σ_y were computed as described earlier (Raynor *et al.*, 1975). Plume width and concentration data are listed in Table 3.

As used here σ_y is the mean of the individual measures of σ_y computed from successive traverses across the plume at a single distance x from the source. It is thus the mean of several (4–8 min) short period measurements.

The standard deviation $\Sigma\sigma_y$ of the summation of all the individual traverses includes meander of the plume as well as diffusion. It is representative of plume width over a measuring period of 30–60 min.

The standard deviation $M\sigma_y$ of the distribution of the centerlines of the plumes on successive passes describes the width of the plume due to meander alone without diffusion.

The various measurements of plume width obtained must be interpreted with respect to conditions observed during the experiments. In most cases, the bottom of both plumes had reached the water before the distance at which measurements were taken. In some tests, however, the centerline of the boat plume or the whole plume remained aloft for appreciable distances or looped

TABLE 2. Turbulence data.

Test no.	10 m $\bar{u}$ (m s^{-1})	Over water σ_θ (deg)	σ_ϕ (deg)	σ_u (m s^{-1})	σ_v (m s^{-1})	σ_w (m s^{-1})	6 m $\bar{u}$ (m s^{-1})	Over island σ_θ (deg)	σ_ϕ (deg)	σ_u (m s^{-1})	σ_v (m s^{-1})	σ_w (m s^{-1})
1	8.08	7.4	5.3	1.22	1.04	0.74	—	21.40	4.00	—	—	—
2	3.12	9.0	4.7	0.54	0.49	0.26	—	—	—	—	—	—
3	0.41	16.7	17.1	0.34	0.12	0.12	—	—	—	—	—	—
4	8.29	4.9	4.5	1.27	0.71	0.65	7.82	8.50	3.40	—	1.15	0.46
5	8.73	3.3	3.0	0.99	0.50	0.46	—	—	—	—	—	—
6	3.00	0.7	—	0.33	0.04	—	2.68	17.50	9.00	—	0.81	0.42
7	5.00	1.7	—	0.27	0.15	—	—	—	—	—	—	—
8	3.05	3.0	2.3	0.45	0.16	0.12	6.00	7.20	4.80	—	0.75	0.50
9	10.31	6.8	3.0	0.36	1.22	0.54	—	—	—	—	—	—
10	4.50	4.2	5.1	0.45	0.33	0.40	—	—	—	—	—	—
11	6.19	2.9	3.1	0.49	0.31	0.33	—	—	—	—	—	—
12	5.87	—	2.6	0.50	—	0.27	5.30	—	9.10	1.40	—	0.84
13	6.51	2.3	1.4	0.32	0.26	0.16	—	—	—	—	—	—
14	6.50	—	5.9	1.05	—	0.67	7.40	—	2.90	1.30	—	0.48
15	8.04	1.7	2.3	0.23	0.24	0.32	6.80	—	4.50	1.10	—	0.53
16	7.93	—	2.4	1.09	—	0.33	—	—	—	—	—	—
17	4.08	2.3	1.3	0.37	0.16	0.09	4.60	—	1.60	1.70	—	0.13
18	5.59	3.1	1.4	0.29	0.30	0.14	7.20	—	2.80	0.60	—	0.35
19	—	—	—	—	—	—	2.10	—	8.80	1.20	—	0.31
20	—	5.7	2.4	—	—	—	—	—	—	—	—	—
21	—	3.9	3.4	—	—	—	—	—	—	—	—	—

TABLE 3. Diffusion results.

Test no.	Source	Q' (g s^{-1})	X (km)	σ_y (m)	$\Sigma\sigma_y$ (m)	$M\sigma_y$ (m)	CWI (mg m^{-2})	χ_{max} $\times 10^{-2}$ (mg m^{-3})	χ_P $\times 10^{-2}$ (mg m^{-3})
1	Boat	2.69	0.70	193.4	341.0	280.9	22.7	12.2	2.7
	Island	2.21	0.40	97.9	168.3	136.9	10.4	5.6	2.5
2	Boat	1.09	0.90	30.4	129.3	125.7	1.5	0.9	0.5
	Island	2.95	1.10	120.3	363.5	343.0	2.7	1.3	0.3
4	Boat	2.44	0.30	52.6	106.5	92.6	8.4	14.2	3.1
	Island	3.91	0.20	57.5	108.8	92.4	20.5	22.0	7.5
5	Boat	2.42	1.00	86.2	146.9	119.0	5.7	21.9	1.6
	Island	4.20	0.90	89.6	142.8	111.3	11.1	4.4	3.1
6	Boat	3.21	1.10	74.1	154.6	135.7	6.1	4.0	1.6
	Island	4.19	1.40	91.1	212.9	192.4	4.3	2.4	0.8
7	Boat	3.73	2.00	117.4	314.6	291.9	4.2	2.1	0.5
	Island	2.29	2.30	147.3	303.6	265.4	2.7	0.8	0.4
8	Boat	5.99	1.60	104.6	250.7	227.8	14.3	9.4	2.3
	Island	3.37	1.80	121.6	230.0	195.2	7.6	3.8	1.3
9	Boat	2.66	0.90	73.8	147.2	127.3	3.9	3.3	1.1
	Island	2.01	0.60	100.3	252.7	232.0	4.9	2.7	0.8
10	Boat	2.09	1.50	59.9	79.8	52.6	7.6	2.5	3.8
	Island	2.18	1.80	71.0	181.5	167.0	1.4	0.4	0.3
11	Boat	2.36	0.90	70.3	241.8	231.3	17.5	14.9	2.9
	Island	2.31	0.70	73.4	568.9	564.2	4.3	3.0	0.3
12	Boat	2.43	0.90	56.3	131.5	118.8	12.6	9.0	3.8
	Island	4.48	0.50	74.0	96.8	62.5	71.6	61.3	29.5
13	Boat	2.43	2.10	58.2	194.2	185.3	11.2	9.5	2.3
	Island	4.48	1.60	62.3	93.6	69.9	49.8	33.3	21.2
14	Boat	2.60	1.10	56.6	74.0	47.7	10.7	9.5	5.8
	Island	2.77	1.10	56.5	110.7	95.2	4.7	4.8	1.7
15	Boat	2.60	2.40	56.8	81.2	58.0	6.1	5.2	3.0
	Island	3.70	2.10	62.6	78.0	146.6	4.7	3.5	2.4
16	Boat	2.60	1.10	68.4	114.6	92.0	34.6	24.6	12.0
	Island	3.70	1.40	70.6	138.3	118.9	23.6	16.6	6.8
17	Boat	2.80	1.80	54.3	109.7	95.3	23.5	20.2	8.5
	Island	2.83	1.60	51.5	74.3	53.5	21.4	29.5	11.5
19	Boat	2.75	1.20	109.2	274.5	251.8	26.2	12.8	3.8
	Island	3.29	0.80	111.1	195.9	161.4	44.0	26.0	9.0
20	Boat	3.20	0.10	39.2	63.3	57.2			
21	Boat	3.20	1.40	86.0	195.0	175.1			

vertically so that some traverses were made below rather than through the plume. These traverses failed to give measurements of plume width or concentration. When averaged with other cases, however, the resulting values are representative of average widths of surface level plumes although not of the actual width at the height of the vertical centerline. Thus, some of the mean plume widths from the boat plume are smaller than they would have been if measurements had been made at centerline height.

On the other hand, it was observed that the plume from the island sometimes meandered less than that from the boat since the island appeared to damp out some of the horizontal direction fluctuations. In these cases, $\Sigma\sigma_y$ and $M\sigma_y$ were greater for the boat plume, although σ_y was less.

Values of σ_y from the plume measurements are plotted as a function of distance in Fig. 4. Much scatter is evident and the trend with distance is not pronounced due to the factors mentioned above. Thus, curves are not fitted to the data. Both the boat and island data range widely with respect to the Pasquill predictions (Hilsmeier and Gifford, 1962) from greater than A to less than F. However, most of the boat plume values fall between C and F and most of the island plume measurements between A and D. Thus, even the over-water plumes average wider than those measured off the south shore of Long Island (Raynor *et al.*, 1975) but conditions were generally less stable in this set of experiments.

Analyses of aerial photographs taken periodically during flights directly along the plume gave many additional values of σ_y using methods described earlier (Raynor *et al.*, 1975). Most of these plume measurements were closer to the source than the densitometer measurements and the two sets of data are shown combined in Fig. 5 with the least squares lines of best fit and the Pasquill A and F curves for reference. Here, the curves more nearly parallel the Pasquill curves and are undoubtedly more representative of actual plume width than the densitometer measurements alone.

For each stability class, σ_y of the island plume is greater than that of the boat plume but the data do not separate well by stability. Equations and correlation coefficients for each curve are given in the figure caption. For comparison, the equation for all boat data combined is $\sigma_y = 0.077X^{0.862}$, $r = 0.752$ and for all island data combined is $\sigma_y = 0.104X^{0.911}$, $r = 0.856$.

A further comparison can be made by taking ratios of the mean values of the boat and island σ_y curves at selected distances. For unstable conditions, the ratio island σ_y/boat σ_y is 2.52 at 100 m and 1.32 at 1 km. For neutral conditions, the ratios are 1.83 and 1.87 and for stable cases, 1.26 and 2.21 respectively. Thus, as shown in Fig. 5, the experimental curves converge under unstable conditions, remain about parallel under neutral cases and diverge with stable conditions. However, these results may be influenced by the limited number of tests obtained.

The difference between stable and unstable cases can better be seen by examining a representative test of each type with good data (Fig. 6). Under unstable conditions (Run 6), the two curves are parallel, close together and have a steep slope. The island plume is about 50% wider than the boat plume. Under stable conditions (Run 13), the curves are also parallel but much farther apart and with shallower slopes. Here, the island plume is nearly four times as wide as the plume from the boat.

Width of both plumes showed a reasonably good relationship to both σ_θ and $\sigma_v/\bar{u}$ as measured from flow over the ocean. Too few turbulence measurements were obtained over the island to make good comparisons between them and width of the island plume. However, on those few days when σ_y measurements were available

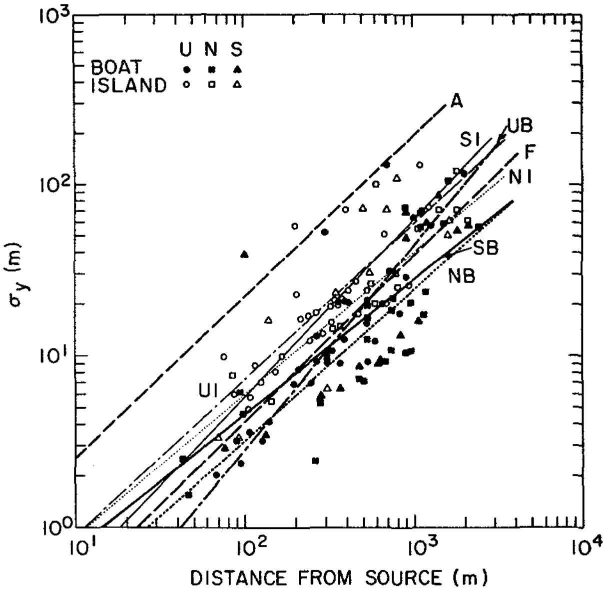

FIG. 5. Plume widths σ_y from densitometer measurements and plume photographs as a function of stability and distance from the source. The Pasquill A and F curves are shown for reference. The curves have the following equations and correlation coefficients:

Unstable boat (UB)	$\sigma_y=0.012X^{1.19}$	$r=0.885$
Neutral boat (NB)	$\sigma_y=0.058X^{0.877}$	$r=0.845$
Stable boat (SB)	$\sigma_y=0.127X^{0.783}$	$r=0.686$
Unstable island (UI)	$\sigma_y=0.108X^{0.914}$	$r=0.859$
Neutral island (NI)	$\sigma_y=0.102X^{0.886}$	$r=0.881$
Stable island (SI)	$\sigma_y=0.052X^{1.027}$	$r=0.859$

from both plumes and σ_θ measurements available from both masts, σ_θ over the island averaged 2.3 times that over the ocean while σ_y from the island plume averaged 2.1 times that of the boat plume. An even better rela-

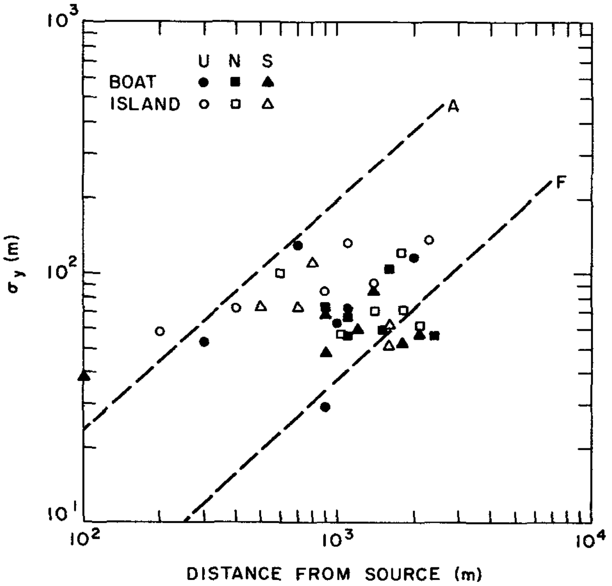

FIG. 4. Plume widths σ_y from densitometer measurements as a function of distance from the source. The Pasquill A and F curves are shown for reference.

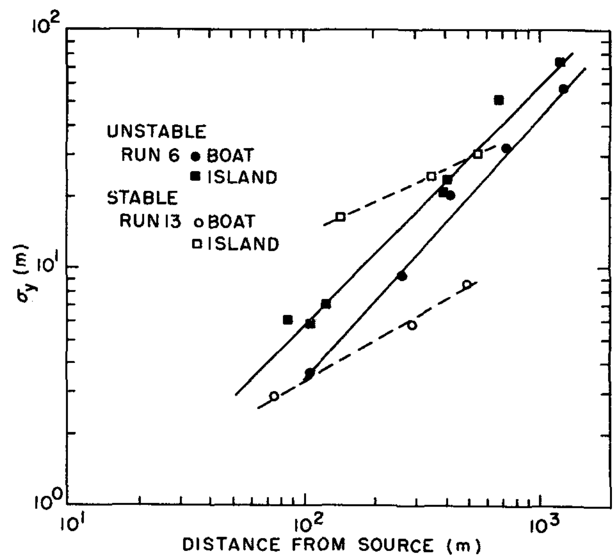

FIG. 6. Plume widths σ_y from plume photographs as a function of distance from the source for selected stable and unstable cases.

tionship might have been found if both σ_y and the turbulence parameters had been measured for the identical time periods but for instrumental reasons the turbulence measurements were typically computed for somewhat shorter time periods within the period of plume measurements.

In those three tests in which the boat plume was allowed to cross the island little additional widening above that occurring by diffusion over the water was evident. Instrumental measurements upwind and downwind of the island were obtained in only one test but aerial photographs were taken in all three. Each test was conducted with stable conditions over the water. Thus, the effect of an obstacle on a plume may be minimal under some conditions.

Values of $\Sigma\sigma_y$ from the boat plumes varied from 1.3 to 4.3 times greater than values of σ_y with a mean ratio of 2.3. From the island plumes, the mean was also 2.3 and the range 1.2 to 7.8.

Values of $M\sigma_y$ from the boat plume ranged from 0.8 to 4.1 times σ_y and averaged 2.0. The island plume ratios had an identical mean and extremes of 0.7 and 7.7

Neither ratio differed significantly between stable and unstable cases indicating that low frequency wind direction fluctuations and consequent plume meander were present under both regimes. The data also show that over a period of time meander may contribute more to the lateral spread of material than diffusion, even under unstable conditions. It is suspected that some plume meander under stable and neutral conditions may be caused by gravity waves (SethuRaman, 1977) and roll vortices, respectively.

Both $\Sigma\sigma_y$ and $M\sigma_y$ showed poor relationships to distance. However, both showed reasonably good agreement with σ_θ and $\sigma_v/\bar{u}$, since both the plume behavior and turbulence measurements respond to the same mean wind direction fluctuations and measuring periods were similar, although not completely simultaneous or of identical length.

f. Plume height

The standard deviation of the vertical distribution of material in the plume (σ_z) was selected as a measure of plume height. Instrumental measurements were not obtained but measurements were made from plume photographs as described earlier (Raynor *et al.*, 1975). Assuming a Gaussian vertical distribution, estimates were also made from the equation

$$\sigma_z = (2/\pi)^{\frac{1}{2}}(Q'/\bar{u}\ \mathrm{CWI}) \qquad (1)$$

where Q' is the smoke output rate (g s^{-1}), $\bar{u}$ is the mean wind speed (m s^{-1}) and CWI is the crosswind integrated concentration (g m^{-2}).

Values of σ_z from photographs of the boat and island plumes are shown in Fig. 7 with the best fit least squares curves and the correlation coefficients. No photographs

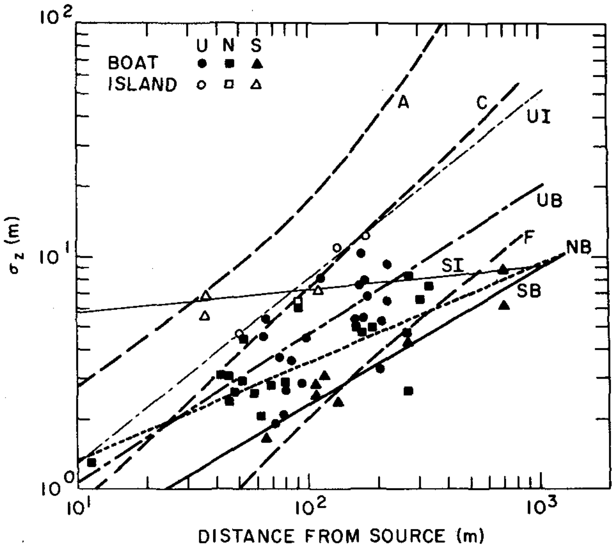

FIG. 7. Plume heights σ_z from plume photographs as a function of distance from the source and stability. The Pasquill A, C and F curves are shown for reference. The curves have the following equations and correlation coefficients:

Unstable boat (UB)	$\sigma_z=0.253X^{0.637}$	$r=0.587$
Neutral boat (NB)	$\sigma_z=0.531X^{0.418}$	$r=0.818$
Stable boat (SB)	$\sigma_z=0.167X^{0.578}$	$r=0.962$
Unstable island (UI)	$\sigma_z=0.205X^{0.796}$	$r=0.978$
Stable island (SI)	$\sigma_z=4.047X^{0.125}$	$r=0.660$

of the island plume were obtained under neutral conditions. For reference, the Pasquill A, C and F curves are included. Slopes are mostly flatter than those of the Pasquill curves. The unstable island curve is close to the C curve but is based on only three points as is the very flat stable island curve. The three boat curves show the expected separation with stability at moderate distances but intersect either close to or distant from the source. The island plumes are appreciably wider than those from the boat except for the intersection of the stable curves near 1000 m.

Values of σ_z were computed by equation (1) for both plumes and plotted as functions of distance from the source. Under unstable conditions, both curves have slopes of 1.0 and nearly identical intercepts. The island data have a correlation coefficient of 0.87 and the boat data 0.66. Under stable and neutral conditions, the island curve had a slope of 0.62 and the boat curve 0.25. Both correlation coefficients were low. These results appear due to the elevated and looping plumes not adequately sampled during boat traverses. However, the values are probably representative of average surface plumes under these conditions.

A representative and commonly used equation for computing effective σ_z in the wake of a structure was given by Slade (1968) as

$$\Sigma_z = (\sigma_z^2 + \mathrm{CA}/\pi)^{\frac{1}{2}} \qquad (2)$$

where Σ_z is effective σ_z, C is a constant relating the size of the obstacle to plume enlargement in its wake and A

is a characteristic dimension of the obstacle, such as cross-sectional area, normal to the wind. Instead of A, Yanskey *et al.* (1966), in a similar formula, used the square of the maximum height of any building adjacent to the source.

Plume height measurements from the island and boat sources were used to compute C using the height of the island at the source location. Cross-sectional area was not used since the length of the island is too great to have a significant effect on vertical motions during flow across its width. Computed values of C and related parameters are shown in Table 4. Values of C are mostly larger than those used previously derived from data on land-based structures ($\sim 0.5-2.0$). This may indicate that an obstacle has a relatively larger effect over the water where the undisturbed plume diffuses more slowly than over land. However, similar values of C are not necessarily applicable to a man-made structure in the water having a different shape and roughness.

The data suggest that C may not be a constant since they clearly show an increase in C with measuring distance. The data from single tests also suggest that C may vary with release location on the obstacle, which seems physically plausible, and possibly with stability.

Yanskey *et al.* (1966) suggested that Σ_z should not be used beyond the point where it equals $3^{\frac{1}{2}}\sigma_z$ on the assumption that the effect of the obstacle becomes negligible at that distance. As shown in Table 4, Σ_z from our data exceeds $3^{\frac{1}{2}}\sigma_z$ in all cases suggesting that the wake effect extends to greater distances. However, the differences are small and if $3^{\frac{1}{2}}\sigma_z$ had been used in place of Σ_z, values of C would be only slightly smaller.

Obviously, much more information is needed before realistic values of C can be specified for an obstacle in the water. Although our data are too sparse for even tentative conclusions, they reinforce Gifford's (1976) remarks on the inadequacy of present knowledge and the need for further study of the problem.

A similar analysis was not performed to determine C from σ_y data since the length of the island was effectively infinite with respect to the source size and comparable to the distances over which measurements were made.

g. *Plume shape*

Measurements of both σ_z and σ_y from plume photographs were obtained for six tests from the boat plume and five tests for the island plume. Ratios of σ_z/σ_y at the same distance varied from 0.50 to 4.13 and averaged 1.53 for the boat plume. Ratios ranged from 0.84 to 6.62 and averaged 2.60 for the island plume. However, these averages are inflated by a few large numbers and are not believed representative of the whole test series. The ratio was near unity in the two unstable cases obtained, less than one for most stable cases but greater than one for the neutral cases and for one stable plume from the island. The height of the plume during neutral conditions is increased by looping in addition to diffusion. On two days, one stable and one neutral when ratios were obtained from both plumes, the ratio from the boat plume was somewhat greater (10–20%) in each case, indicating that the island induced more lateral than vertical growth in its plume. The $\sigma_\phi/\sigma_\theta$ ratio was obtained at both masts on only one of those two days but was about 15% greater over the water than over the island giving some confidence that turbulence data can be used to predict plume shape.

h. *Normalized concentrations*

Normalized concentrations were computed by three methods and related to source location, distance and stability (Table 3).

$\chi_{max}\bar{u}/Q'$ (m^{-2}) is the mean maximum centerline concentration, χ_{max} (gm m^{-3}) for all passes across the plume at a single distance, multiplied by the mean 10 m wind speed, $\bar{u}$, (m s^{-1}) and divided by the output rate, Q', (g s^{-1}). It is representative of fairly short sampling periods.

TABLE 4. Values of building wake constant C and related parameters.
A. From curves of Fig. 7

Distance from source (m)	h(m)	Σ_z(m)	σ_z(m)	$\sqrt{3}\sigma_z$(m)	C
50	10	6.0	2.7	4.7	0.90
100	10	8.0	3.7	6.4	1.58
500	10	15.8	7.8	13.5	5.93
1000	10	21.0	10.8	18.7	10.18

B. From single tests

Distance from source (m)	Test no.	Stability	Source location	h(m)	Σ_z(m)	σ_z(m)	$\sqrt{3}\sigma_z$(m)	C
100	8	Neutral	Downwind	6	6.5	3.3	5.7	2.73
200	12	Stable	Center	12	16.0	8.8	15.2	3.93
1000	13	Stable	Center	12	20.0	9.4	16.3	6.86

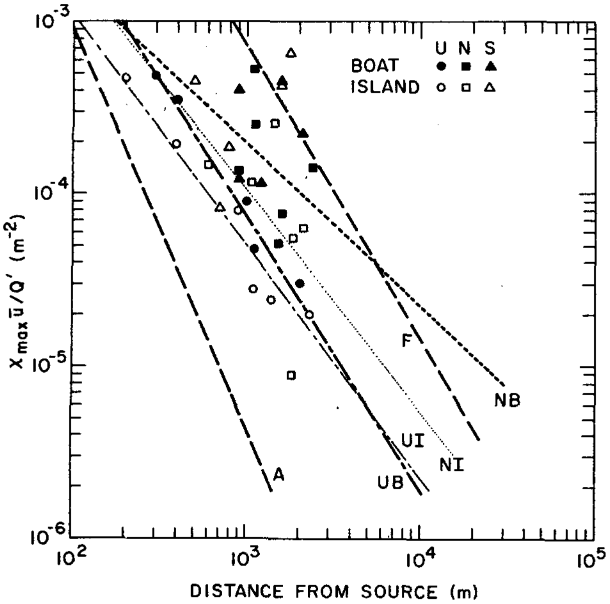

FIG. 8. Normalized maximum centerline concentration from boat and island sources as a function of distance from the source and stability. The Pasquill A and F curves are shown for reference. The curves have the following equations and correlation coefficients:

Unstable boat (UB)	$\chi\bar{u}/Q'=3.85X^{-1.577}$	$r=-0.973$
Neutral boat (NB)	$\chi\bar{u}/Q'=0.149X^{-0.960}$	$r=-0.404$
Stable boat (SB)	$\chi\bar{u}/Q'=1.44\times10^{-5}X^{0.384}$	$r=-0.220$
Unstable island (UI)	$\chi\bar{u}/Q'=0.843X^{-1.411}$	$r=-0.974$
Neutral island (NI)	$\chi\bar{u}/Q'=0.767X^{-1.286}$	$r=-0.511$
Stable island (SI)	$\chi\bar{u}/Q'=1.77\times10^{-6}X^{+0.742}$	$r=-0.491$

CWI $\bar{u}/Q'$ (m^{-1}) is similar except that the crosswind integrated concentration is used instead of the maximum centerline concentration. By integrating in the crosswind, only vertical diffusion changes the value with distance.

A third formulation is $\chi_p\bar{u}/Q'$ (m^{-2}), where

$$\chi_p=\mathrm{CWI}/(2\pi)^{\frac{1}{2}}\Sigma\sigma_y. \qquad (3)$$

χ_p is the estimated peak concentration one would obtain from a Gaussian plume with a standard deviation equal to $\Sigma\sigma_y$ and a CWI equal to the mean CWI from a series of sequential traverses at a single distance. It is representative of peak concentrations over longer time periods under conditions of plume meander.

Values of $\chi_{max}\bar{u}/Q'$ are shown as a function of distance from the source in Fig. 8 with the least squares lines of best fit. The equations of the curves and the correlation coefficients are given in the caption. Nearly all data fall between C and F with a few cases above F from both sources. Slopes are somewhat flatter than those of the Pasquill curves, two of which are given for reference. The unstable curves are quite similar but the neutral curves show higher concentrations from the boat than from the island. Curves are not fitted to the data from stable cases since they do not decrease with distance.

Use of CWI $\bar{u}/Q'$ gives similar results. Very good agreement is found for unstable cases and rather poor for stable and neutral cases. When all cases are combined, the slope of the boat plume curves is -0.54 and the island plume curves -0.91, which results in crossing of the curves at about 400 m. At greater distances, concentration of the boat plume increasingly exceeds that of the island plume reaching a factor of more than 3 at 10 km.

The formulation $\chi_p\bar{u}/Q'$ gave small values when normalized by wind speed and output rate, since χ_p is always smaller than χ_{max} (Table 3) and showed little variation with distance in stable and neutral cases. This results from a CWI nearly constant with distance on the average which implies little vertical diffusion. Since χ_p is also a function of $\Sigma\sigma_y$, which is largely a measure of plume meander, this suggests that horizontal diffusion is not as important as meander in determining plume widths over periods of an hour or longer under such conditions.

Under unstable conditions, however, a definite dependence on distance is evident. The boat plume curve has a slope of -1.46 and the island plume -1.44. Under unstable lapse rates, vertical diffusion is more important so that CWI decreases with distance faster than $\Sigma\sigma_y$ and χ_p becomes smaller. Concentrations were similar in both plumes.

5. Conclusions

Diffusion conditions were well categorized by both mast and aircraft level temperature profiles and by σ_θ and σ_ϕ measurements but not quite as well be the bulk Richardson number which is sensitive to small measurement errors.

Width of the island plume was about 1.5 times that of the boat plume during unstable conditions, 4 times during neutral and stable conditions and 2 times during the mix of conditions studied. $\Sigma\sigma_y$, which includes meander as well as diffusion of the plume, averaged 2.3 times greater than σ_y for both sources. It ranged from 1.3 to 4.3 times greater for the boat plume and 1.2 to 7.8 times greater for the island plume. $M\sigma_y$, which results only from meander of the plume, averaged 2.0 times σ_y for both sources and varied from 0.8 to 4.1 times greater for the boat plume and 0.7 to 7.7 times greater for the island plume. Thus, meander contributed more to dispersion of both plumes than diffusion, particularly during neutral and stable conditions.

Height of the island plume averaged about twice that of the boat plume. The wake coefficient C for the island falls in the range of 1 to 10 but appears to vary with downwind distance and with position of the release point on the obstacle.

Normalized maximum centerline concentrations χ_{max} from the boat plume were 1.2–2.0 times greater than from the island plume but averaged 1.4 during unstable periods and about 2 during stable and neutral conditions.

Normalized crosswind integrated concentrations, CWI, were nearly identical from both plumes during unstable conditions since vertical diffusion was similar. Under stable and neutral conditions, concentration of the boat plume became increasingly greater than that of the island plume at downwind distances greater than 0.4 km apparently due to increased vertical diffusion of the island plume.

Normalized longer period concentrations, χ_p, show little change with distance during stable periods since vertical diffusion is minimal and meander contributes heavily to lateral dispersion. In unstable conditions, a decrease with distance occurs but the two plumes behave in similar fashion since meander predominates in both.

Considering all measures of dispersion, the plume from the island disperses about twice as fast as that from the boat during unstable conditions but as much as four times as fast during stable periods.

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REFERENCES

Abbey, R. F., Jr., 1976: Characterization of wakes downwind of nuclear reactors. *Preprints Third Symp. Atmospheric Turbulence, Diffusion and Air Quality*, Raleigh, Amer. Meteor. Soc., 247–254.

Barry, P. J., 1964: Estimation of downwind concentration of airborne effluents discharged in the neighborhood of buildings. Rep. AECL-2043, Atomic Energy of Canada, Ltd., Chalk River, Ontario, 15 pp.

Brown, R. M., L. A. Cohen and M. E. Smith, 1972: Diffusion measurements in the 10–100 km range. *J. Appl. Meteor.*, **11**, 323–337.

Culkowski, W. M., 1967: Estimating the effect of buildings on plumes from short stacks. *Nucl. Safety*, **8**, 257–259.

Davies, P. O. A. L., and P. L. Moore, 1964: Experiments on the behavior of effluent emitted from stacks at or near the roof level of tall reactor buildings. *Int. J. Air Water Pollut.*, **8**, 515–533.

Dickson, C. R., G. E. Start and E. H. Markee, Jr., 1967: Aerodynamic effects of the EBR-II containment vessel complex on effluent concentration. *Proc. USAEC Meteorological Information Meeting*, C. A. Mawson, Ed., Rep. AECL-2787, Atomic Energy of Canada, Ltd., Chalk River, Ontario, 86–101.

Gifford, F. A., 1976: Turbulent diffusion-typing schemes: a review. *Nucl. Safety*, **17**, 68–86.

Halitsky, J., 1968: Gas diffusion near buildings. *Meteorology and Atomic Energy*, D. A. Slade, Ed., USAEC Rep. TID-24190, 221–225 [Available from NTIS].

Hansen, A. C., J. A. Peterka and J. E. Cermak, 1974: Wind-tunnel measurements in the wake of a simple structure in a simulated atmospheric flow. Rep. CER73-74 ACH-JAP-JEC43, Colorado State University, 39 pp.

Hilsmeier, W. F., and F. A. Gifford, Jr., 1962: Graphs for estimating atmospheric diffusion. USAEC Rep. ORO-545, Weather Bureau, Oak Ridge, Tenn., 10 pp.

Hinds, W. T., 1967: On the variance of concentration in plumes and wakes. Rep. BNWL-SA-1435, Pacific Northwest Laboratory, Richland, Wash., 67 pp.

Huber, A. H., and W. H. Snyder, 1976: Building wake effects on short stack effluents. *Preprints Third Symp. Atmospheric Turbulence, Diffusion and Air Quality*, Raleigh, Amer. Meteor. Soc., 235–242.

Islitzer, N. F., 1965: Aerodynamic effects of large reactor complexes upon atmospheric turbulence and diffusion. Rep. IDO-12041, National Reactor Testing Station, Idaho Falls, 15 pp.

Meroney, R. N., 1971: Gaseous plume diffusion about isolated structures of simple geometry. Rep. CER71-72, RNM19, Colorado State University, 13 pp.

——, and J. E. Cermak, 1967: Wind tunnel modeling of flow and diffusion over San Nicolas Island, Calif., Rep. CER-66-67 RNM-JEC44, Colorado State University, 97 pp.

——, ——, J. R. Connell and J. A. Garrison, 1974: Wind engineering study of atmospheric dispersion of airborne materials released from a floating nuclear power plant. Rep. CER74-75 RNM-JEC-JRC-JAG4, Colorado State University, 266 pp.

Munn, R. E., and A. F. W. Cole, 1967: Turbulence and diffusion in the wake of a building. *Atmos. Environ.*, **1**, 133–143.

Offshore Power Systems, 1973: Generic environmental report. Supplement to manufacturing license application, Westinghouse-Tenneco.

Prophet, D. T., 1961: Survey of the available information pertaining to the transport and diffusion of airborne material over ocean and shoreline complexes. Tech. Rep. No. 89, Aerosol Lab., Stanford University, 53 pp.

Raynor, G. S., P. Michael, R. M. Brown and S. SethuRaman, 1975: Studies of atmospheric diffusion from a nearshore oceanic site. *J. Appl. Meteor.*, **14**, 1080–1094.

Sagendorf, J. F., 1974: A program for evaluating dispersion from a nuclear power station. NOAA Tech. Memo ERL ARL-42, 12 pp. [Available from NTIS].

SethuRaman, S., 1977: The observed generation and breaking of atmospheric internal gravity waves over the ocean. BNL Rept. 22345. (*Bound.-Layer Meteor.*, in press.)

——, and Raynor, G. S., 1975: Surface drag coefficient dependence on the aerodynamic roughness of the sea. *J. Geophy. Res.*, **80**, 4983–5088.

Slade, D. H. (Ed.), 1968: *Meteorology and Atomic Energy 1968*. Rep. TID-24190, 1970 Printing, U. S. Atomic Energy Commission, Washington, D. C., 445 pp.

Van der Hoven, I., 1967: Atmospheric transport and diffusion at coastal sites. *Nucl. Safety*, **5**, 490–499.

Yang, B. T. and R. N. Meroney, 1970: Gaseous dispersion into stratified building wakes. Rep. CER70-71 BTY-RNM-8, Colorado State University, 103 pp.

Yanskey, C. R., E. H. Markee, Jr. and A. P. Richter, 1966: Climatography of National Reactor Testing Station. USAEC Rep. IDO-12048, 222 pp.