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Wind-Tunnel Measurements of Dispersion and Turbulence in the Wakes of Nuclear Reactor Plants

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ABSTRACT

Between 1975 and 1979 via contracts between the Nuclear Regulatory Commission and Colorado State University a sequence of laboratory experiments have been performed to evaluate the influence of nuclear reactor building complexes on dispersion of effluents released into their wakes. This study involved research directed toward quantifying the wake-dispersion interaction as well as a validation exercise to compare laboratory and field measurements about specific sites.

This report presents the program objectives and summarizes the results of two model/field building dispersion experiments; a comparison of perturbation model predictions to model measurements of velocity deficit, turbulence excess, and temperature or concentration perturbations; an examination of the efficacy of a new algorithm used to predict full scale concentrations downwind of buildings in nonstationary wind fields from wind tunnel measurements; preliminary measurements of close in dispersion near obstacles; and behavior of a stratification wind tunnel designed to study coastal atmospheric boundary layer behavior.

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Symbol	
A	Reference area or building cross-section
Fr_δ	Froude Number based on boundary layer depth
H	Building height
HR	Heating ratio
K	Dimensionless concentration coefficient
Re	Reynolds Number
Ri_B	Bulk Richardson Number
$\overline{t}_s$	Effective average sampling time
U_{rms}	Turbulence velocity
U_*	Friction velocity
U_H	Reference wind velocity at building height
x	Downwind distance
Z_s	Source height
Z_o	Roughness length
β α τ	Power law coeffients of χ variation
δ	Boundary layer depth

ACKNOWLEDGMENT

This study was performed under Contract No. AT(49-24)-0236 with the Office of Nuclear Regulatory Research Branch of the United States Nuclear Regulatory Commission. Financial assistance received is gratefully acknowledged. The guidance of Dr. Robert F. Abbey, Jr., Nuclear Regulatory Commission, in coordinating this effort with the field program at the Idaho National Engineering Laboratory and the Rancho Seco Nuclear Power Station, California, was essential to the completion of this program. Field data provided by C. R. Dickson and his colleagues at NOAA/Air Resources Laboratory, Idaho Falls, Idaho, is gratefully acknowledged.

1.0 INTRODUCTION

Nuclear power reactors are generally enclosed in an airtight shell [illegible]revents arbitrary release of radioactive gases to the at[illegible]wever, in normal operation of some reactor [illegible]ions the air around and within a reactor becomes contaminated with radioactive isotopes of such gases as argon, xenon, krypton, and the halogens. It is a general practice to store the contaminated products until such time that meteorological conditions are favorable for dilution and dispersion. In the event of a power excursion or accident, however, it may be necessary to make a release in meteorologically unfavorable conditions.

It has been a traditional design technique to release polluted gases through roof top vents or short stacks located near the reactor. Calculation of peak and mean ground concentrations are then based on some semi-empirical model which relates the release rate from an elevated point source to the concentration at some point downwind.

In the future, however, it may be desirable, due to aesthetics, cost and public relation reasons, to utilize a shorter stack or vent connected directly to the reactor building. In these cases plume dispersion is sufficiently modified by the presence of the local building structure or ground topography that one approach available is that of wind-tunnel model tests. When the stack height is such that the effluent is discharged near the cavity boundary, the momentum of the effluent may or may not be such that the gas is projected beyond the cavity separation streamline.

If the contamination remains within the cavity-wake region the average concentration may be approximately predicted by semi-empirical expressions primarily derived from previous wind-tunnel experiments. In the event the gas does initially penetrate the cavity boundary there is still the possibility that the lower edge of the expanding plume may re-enter the cavity-wake region and provide a secondary source of building and ground contamination.

Only in the period since 1958 have there been published experimental data on concentrations close to buildings suitable for extrapolation to full scale prototype situations. These measurements include only a limited number of geometries and release conditions. Buildings consisting of rounded or curved external surfaces have in particular received limited attention, yet cylindrical containment structures are commonly proposed for a nuclear power reactor. In addition, recent architectural practice tends to favor the introduction of compound curves for building shapes.

It is generally accepted that atmospheric stratification should be only a secondary significance on dispersion in cavity and wake fields of building structures. Nevertheless, public safety suggests that any estimate concerning increased dilution in the wake of structures be considered with caution. It has been suggested that stable conditions might decrease mixing or entrainment in the cavity and increase ground-level concentrations.

Finally, recent practice in reactor construction includes the release of off-gases or minor effluents through short stacks of ventilation shafts. Can the hazard analysis safely give credit for this increased height and subsequent potential increased dilution in estimation of ground level concentrations?

Building and building complexes immersed in the atmospheric boundary-layer winds produce non-uniform fields of flow and turbulence which can significantly modify the dispersion of a source in the vicinity of the complex. Diffusion in the turbulent cavity-wake regions of a building has been studied both in the field and wind tunnel with increasing interest during the past twenty years. Table I provides a comparison of the conditions under which the more recent and detailed laboratory and field measurements have been obtained. Ground level plume centerline concentration versus downwind distance for a number of these studies has been qualitatively considered by Abbey (1976); nevertheless the data have yet to be uniformly normalized with respect to surface roughness, complex cross-section, sample averaging time, stability, auxiliary buildings, plume release height, etc. Smith (1975) and Robins (1975) have compared short stack behavior with Meroney and Yang (1971) and found good agreement for cube structures in the near field ($x \leq 5H$). The results of Huber and Snyder (1976) and Robins (1975) are consistent in the far field ($x \geq 5H$). Halitsky's pre-construction model study of the EBR-II in Idaho completed in 1963 agrees qualitatively with the field measurements over the comparable near field where measurements in both test series are available. Unfortunately the reactor complex as finally constructed contained additional buildings and the large power plant building was at a different equivalent height than in the model (Halitsky, 1975).

Gifford (1960) modified the basic ground level Gaussion plume model to include an initial dilution; Yanskey, Markee and Richter (1966) proposed a model based on modification of the plume standard deviations, and Turner (1970) proposed a displaced virtual source method to account for building plume interaction. For short stacks in

TABLE 1

EXPERIMENTS ON DIFFUSION IN THE WAKE OF SIMPLE BUILDING COMPLEX

Investigator	Building Complex (scale)	$\frac{z_o}{H} \times 10^3$	$\frac{u_*}{U_H}$	$\frac{u_{rms}}{U_H}$	Re x 10^{-3}	$\frac{S}{H}$	α^*	$\frac{z_s}{H}$	$\frac{A}{H^2}$	$\frac{x_{min}}{H}$	$\frac{x_{max}}{H}$	Cases Stability			$\frac{K_{max}}{3H}$ #	**			$\bar{t}_s$
												N	S	US		-γ	β	ζ	
Laboratory:																			
Halitsky (1963) (1975)	EBR-II Reactor (1:96)	.5	.053	--	31	3	.15	.1	5	.5	3	6	--	--	1.1	1.9	--	--	10 m
								.6											
								1.0											
Jensen & Frank (1963)	3 Story House (1:170)	400	.32	--	30	6.7	.8	1.1 ↓	3.6	1.0	16	2	--	--	.05	1.6	--	--	--
								1.5								1.0	--	--	
Martin (1965)	Phoenix Memorial Reactor (1:150)	110	.18	--	14	9	.45	1.2	3.3	1	18	4	--	--	.5	.3	--	--	10 m
												--	2	--		.8	--	--	
Yang & Meroney (1970)	Cube	1	.06	.19	14	4	.14	.1	1.0	3	25	12	--	--	2	.68	.50	.3	10 m
		13	10	--			.21	.5				--	18	--	3	.60	.23	.3	
								1.0											
Meroney & Yang (1971)	Cube	1	.06	.19	14	4	.14	1.0	1.0	4	60	4	--	--	1.2	.68	--	--	10 m
Robins (1975)	Cube	22	.11	.27	200	10	.20	.1	1.0	.5	40	32	--	--	1-10	.6	.3	.3	10 m
								.8											
								1.0											
Huber & Snyder (1976)	Block H:W:B = 1,2,1	2	.064	.13	34	7	.17	.1 ↓	2.0	2	30	.25	--	--	.5	.6	1.0	1.0	10 m
								2.5											
ΔHatcher, Meroney, Peterka & Kothari (1978)	TOCR Reactor (1:200)	1.8	.064	.09	12	10	.16	.04	<2.0	1.5	70	27	--	--	.5	1.0	.65	.5	10 m
								1.0				--	54	--	.5	.7	--	--	
								1.3				--	--	27	.5	1.0	--	--	
ΔAllwine, Meroney & Peterka (1978)	Rancho Seco Reactor (1:500)	3	.049	.10	7.5	6	.1-	0.9	1.5	2	15.4	32	--	--	3.9	1.0	.53	1.0	10 m
							.4	0.4				--	[illegible]	--	6.6	1.0	.44	1.0	
								1.0				--	--	32	5.1	1.0	--	--	

ΔSupported by NRC Contract -04-76-236, #3

TABLE 1 (continued)

EXPERIMENTS ON DIFFUSION IN THE WAKE OF SIMPLE BUILDING COMPLEX

Investigator	Building Complex (scale)	$\frac{z_o}{H} \times 10^3$	$\frac{u_*}{U_H}$	$\frac{u_{rms}}{U_H}$	$Re \times 10^{-3}$	$\frac{\delta}{H}$	α*	$\frac{z_s}{H}$	$\frac{A}{H^2}$	$\frac{x_{min}}{H}$	$\frac{x_{max}}{H}$	Cases Stability			$\frac{K_{max}}{3H}$ @	**			$\overline{t}_s$
												N	S	US		$-\gamma$	β	ζ	
Field:																			
Martin (1965)	Phoenix Memorial Reactor	--	--	--	2	--	--	1.2	3.25	1	18	7	--	--	1.5+	1.2	--	--	5 m
					4							--	4	--	0.5	2.3	--	--	
Islitzer (1965)	TRA Reactor Complex	1.6	.06	--	10	13	.15	.05	5.0	6	43	9	--	--	1.6	1.8	--	--	120-600 m
												--	2	--	2.2	3.0			
Hinds (1969)	Shed (H:W:D) 11 x 24 x 34 m	2.7	.075	.23	2	30	.18	.1	3.0	3	10	2	--	--	2.42	2.0	--	--	5_s-15 m
Dickson et al (1969)	EBR-II Reactor (30 m)	1.3	.06	--	9	10	.15	.03	5.0	4	24	4	--	--	1.0	1.2	.87		30 m
												--	9	--	1.0				
Smith (1975)	Block (H:W:D) 2 x 3.0 x 3.0 m	16+	.10+	.1+	.012+	160+	.13+	1.0+	3.0	.5	5	--	11	--	2.0	--	--	--	5_s-20 m
		350	138	.6	.8	225	.33	2.0				--	--	20					
Abbey (1976)	EOCR Reactor (22.5 m)	1.8	.06	--	10	13	.15	.04	<2.0	2	70	8	--	--	0.35	1.4	--	--	60 m
								1.0				--	12	--					
								1.3											
Start, et al. (1978)	Rancho Seco Reactor (52 m)	0.3	.045	--	12.7×10^3	11	.1-.35	0.0	1.5	2	15.4								60 m
								0.4											

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* $\frac{u}{u_r} = \left(\frac{z}{z_r}\right)^{\alpha}$

** $K_{max} \sim x^{\gamma}$, $\sigma_y \sim x^{\beta}$, $\sigma_z \sim x^{\zeta}$

the presence of buildings Briggs (1973) has recommended plume height adjustments. Variations in these basic approaches have been tried by other authors including adjustments for downwind decay of building wake turbulence. Meroney and Yang (1971), Robins (1975), and Smith (1975) have also provided simple correlations of ground level maximum concentration versus stack height/building height ratio and exhaust/reference stream velocity ratio.

Concern over the ground level concentration patterns (maximum and horizontal spread) which may exist at a reactor site and its boundaries has led to the wind tunnel/field program discussed herein.

2.0 PROGRAM OBJECTIVES

The former Atomic Energy Commission supported a program from 1969 to 1971 at Colorado State University to examine gaseous plume diffusion about isolated structures of simple geometry. The conclusions of that study were reported by Meroney (1971). The study emphasized the measurement of dispersion downwind of simple cubical or cylindrical structures immersed in neutral and stable surface layers and releases from short stacks. The approach isolated the peculiarities of such configurations in an effort to make appropriate field predictions possible.

Stratification was found to freeze plume growth to the dimensions reached after aerodynamic mixing in the building wake. Downwind of $x/H \geq 5$ dispersion is independent of minor building shape variations; however, the building influence is noticeable to 20H. Short stacks were found to improve dilution before ground interception by levels of tenfold over direct interception and entrainment. Orientations of the building to the wind (i.e., $\theta = 45°$) aggravate entrainment and increase ground concentrations.

The 1975-1979 research period has built on the results of this earlier effort. In particular diffusion about specific reactor sites have been examined to validate the physical model method while extending the value of expensive field programs. The physics of the building wake region have been investigated in greater detail. Upon this improved physics could be constructed a realistic prediction model for diffusion estimates as well as velocity, turbulence, and temperature perturbations.

The following outline summarizes the specific program goals and problem areas that were examined during the period 1975-1979. Investigations were pursued:

1. To determine quantitatively the character of dispersion in the wake region behind a model of a simple single building reactor complex (EOCR) situated in flat terrain, and to compare the model measurements to those taken about the prototype building during a field program.

2. To determine quantitatively the character and persistence of the wake region itself under similar conditions.

3. To determine quantitatively the characteristics of dispersion in the wake region behind a model of a complex nuclear reactor station (Rancho Seco) situated in moderately flat, but rolling, terrain; and to compare the model measurements to those taken about the prototype building during a field program.

4. To measure the streamline and turbulence behavior behind simple cubical buildings in neutral and stable stratified shear layers to determine the character of the wake region out to 100 characteristic lengths.

5. To develop appropriate empirical or analytical formulations for building wake behavior capable of predicting velocity, temperature, and turbulence perturbations as well as plume dispersion in the far wake regions ($\frac{X}{H} > 5$) for both idealized shapes and realistic building complexes.

6. To develop a realistic means of comparing physical model diffusion measurements taken at one average sampling time to field measurements taken over different sampling intervals or gustiness conditions.

7. To examine for a simple building configuration the tendency of effluent parcels emitted at one structure to be successively captured by nearby building eddies and pool in their vicinity before moving further downwind.

8. To determine in a preliminary manner the behavior of gases as they mix in the "cavity" region ($\frac{X}{H} < 5$) behind a building. Document the mean concentrations on the building surface as well as cavity cross-section. Examine the instantaneous concentration fluctuations in the cavity area.

9. To examine the character of unstable internal boundary layers developed during flow over warm surface, and to relate the physics on this behavior to dispersion of gases released near city, coastal, or lake boundaries.

It was recognized that the results of wind-tunnel tests over scaled models are often considered with some reserve until their veracity has been checked by a prototype comparison. Hence items 1), 2), 3), 4), 5), and 6) were given priority attention during this research program. To improve data inter-comparisons extensive communication was maintained with the NOAA/Air Resources Laboratory led by C. R. Dickson located at the Idaho National Engineering Laboratory, Idaho Falls. They were responsible for conducting the field prototype studies. The wind-tunnel experiments were designed to develop geometrical, dynamics, and kinematic similarity to the conditions found in the field situations.

Items 7), 8) and 9) were of the nature of feasibility studies. Limited results are summarized herein.

3.0 RESEARCH RESULTS AND REPORT ABSTRACTS

Most of the results of this research program have been reported separately in individual topical reports. The following paragraphs summarize the content of each report, specify its conclusions, and document where the material has appeared in the open literature.

3.1 DISPERSION IN THE WAKE OF A MODEL INDUSTRIAL COMPLEX:

(NUREG-0373) by R. V. Hatcher, R. N. Meroney, J. A. Peterka, and K. M. Kothari, 1978.

Abstract:

1:200 scale models of the EOCR reactor building and surrounding silo and tank buildings at the Idaho National Engineering Laboratory, Idaho Falls, Idaho, were put into the Meteorological Wind Tunnel at Colorado State University for the purpose of studying the effect of building wakes on dispersion. Flow visualization was done and concentration measurements were taken. The text program consisted of 108 systematic releases from ground, building height, and stack height sources with no appreciable plume rise. The program was repeated for cases of moderately unstable, neutral, moderately stable, and stable conditions in the wind tunnel.

Results show that the buildings significantly alter the dispersion patterns and the addition of any extra buildings or slight terrain change in the immediate vicinity of the building has a major effect. In the near wake region the effects of stratification were still evident causing slightly higher concentrations for stable conditions and slightly lower for unstable. Current dispersion models are discussed and evaluated that predict concentrations in the wake region. A simple volume source model was found to predict ground level concentrations reasonably well. No model was found to predict accurately concentrations from elevated sources. In agreement with earlier studies the major effect of the buildings was to enhance the dispersion in both the horizontal and vertical for ground level releases while from elevated releases only the vertical dispersion was enhanced.

Conclusions:

Information about dispersion in the wake of an industrial complex has many practical applications. From the EOCR wind tunnel study the following conclusions can be made:

1. In the near wake region dispersion patterns significantly differ from those without the buildings present and cause concentrations up to 100 percent lower.
2. At some distance downwind, generally by $x/H = 8$, the rate of dispersion is independent of release position and building orientation.
3. Minor additions to the building complex cause significantly altered flow and dispersion patterns but only in preferred orientations.
4. Minor changes in topography near the building also can significantly affect the dispersion patterns by diverting the flow around one part of the building.
5. In the cavity-wake region behind the building aerodynamic turbulence dominates over the atmospheric turbulence but the effects of the latter are still slightly visible in the flow visualization sequences.
6. Further downwind the atmospheric turbulence begins to take over and completely dominates by $x/H = 15$.
7. For $x/H > 15$ concentrations are virtually independent of whether or not the buildings were present.
8. The effects of stratification are to cause slightly higher concentrations for stable atmospheres than a similar release near a building in a neutral environment while slightly lower concentrations are noticed for unstable stratifications.

9. The effect of the buildings is to enhance the dispersion (mostly in the horizontal) and cause lower concentrations. These lower concentrations may be accounted for by the use of either Gifford's (1960) volume source model or the model of Huber and Snyder (1976). Because the latter model requires detailed knowledge of the flow structure in the wake which is sometimes difficult to obtain, Gifford's model appears preferable. Gifford's model, however, cannot account for elevated releases. Huber and Snyder's model underpredicts concentrations very close to the building for elevated releases.

10. Ground level releases in the wake of the structure tend to enhance the dispersion in both the horizontal and vertical, while elevated releases enhance only the vertical. This conclusion was also reached in the previous study by Huber and Snyder (1976).

Published in Open Literature as:

Meroney, R. N., J. A. Peterka, R. V. Hatcher, and K. M. Kothari "Gaseous Dispersion and Turbulence in the Wake of Nuclear Reactor Plants," Proceedings of 4th International Clean Air Congress, Tokyo, Japan, May 16-20, 1977, pp. 167-170.

Hatcher, R. V. and R. N. Meroney, "Dispersion in the Wake of a Model Industrial Complex," Proceedings of Joint Conference on Applications of Air Pollution Meteorology, AMS-APCA, Salt Lake City, Utah, November 1977, pp. 343-346.

3.2 RANCHO SECO BUILDING WAKE EFFECTS ON ATMOSPHERIC DIFFUSION (NUREG/CR-1286) by K. J. Allwine, R. N. Meroney and J. A. Peterka, 1978.

Abstract:

Ninety-six wind tunnel diffusion tests were conducted on 1:500 scale models of the Rancho Seco Nuclear Power Station, California; surrounding buildings, hyperbolic cooling towers, and terrain were similarly modeled in the Meteorological Wind Tunnel at Colorado State University. The purpose was to quantify the effects on diffusion of building perturbing the mean flow. The test program consisted of gaseous tracer releases from two ground

locations, the turbine building top, and containment vessel top. The program was repeated for each wind direction and cases of unstable, neutral and stable atmospheric stratification conditions.

The bulk Richardson numbers set in the wind tunnel were 0.0, 0.35 and -0.32 corresponding to the three stabilities, with power law exponents of 0.15, 0.44 and 0.10, respectively. The roughness length modeled was that of short grass (Z_o = 0.014 m).

Results show that the buildings significantly perturb the dispersion patterns from the flat terrain isolated source release case, hence buildings, hyperbolic towers, and terrain in the immediate vicinity of the release have a major effect. Maximum ground level normalized concentrations occurred during stable stratification. Upwind or downwind presence of the hyperbolic cooling towers was felt by the shift of ground level concentration values toward conditions approximately two categories more unstable than that suggested by the Pasquill-Gifford curves for the background flow stability.

Data from three of the eight wind directions have been examined in some detail. These included 135°, containment building upwind of cooling towers; 225°, cooling towers to the side of the containment vessel wake; and 315°, cooling towers upwind of the containment vessel. If it is assumed that wind tunnel measurements are equivalent to field averaging times of 10 minutes then the model concentrations adjusted to equivalent one-hour field sampling times overpredict field measurements for these cases by at most a factor of 1.7.

Conclusions:

From the Rancho Seco wind tunnel tests the following conclusions were drawn:

1. The maximum ground-level dimensionless concentration coefficient for each of the four sampling arcs occurred during moderately stable stratification. The highest ground-level concentration on all four arcs were measured during the eastern wind direction from release on the containment vessel top. In such an orientation there is maximum interaction with downwind building complex without the diluting effects of the large cooling towers.
2. Plots of lateral and vertical concentration standard deviation (σ_y and σ_z) and dimensionless concentration (K_c) variation with downwind distance compared with Pasquill-Gifford predicted values for different stability categories provided the following general conclusion: For the case of the cooling towers not affecting the plume (225°), the Pasquill-Gifford stability indicated one category more unstable than the approach flow conditions at 800 meters. For the cooling towers directly affecting the plume (135°, 315°), the Pasquill-Gifford category indicated approximately two categories more unstable than the background flow stability.

3. On the 100 meter arc, the Gaussian diffusion equation predicted K_c over-estimates the wind tunnel K_c by a factor of approximately 17. It is believed that the wind tunnel over-predicts a one-hour sampling time prototype K_c by a factor of 2.5 for a near neutral stability. From actual field measurements at the Rancho Seco Facility, the measured ground level centerline concentrations were about 75 times smaller than that predicted by the Gaussian diffusion equation. This implies that for a ground level release the wind tunnel over-predicts the actual field concentrations by a factor of approximately 1.7.
4. On the 100 meter arc, the Gaussian diffusion equation modified by Gifford (1960) ($C = 0.5$) under-predicts the wind tunnel concentration by a factor of 0.7 and at 800 meters the modified Gaussian over-estimated by a factor of 2.7.
5. The horizontal dispersion coefficient, σ_y, was determined using a moment method and the vertical dispersion coefficient, σ_z, was determined from the crosswind integrated average concentration equation. The average σ_y from the Rancho Seco field study is approximately 1.6 times larger than the σ_y from the wind tunnel data. This can probably be attributed to plume meandering. The σ_z for the wind tunnel data is approximately 2.2 times larger than the σ_z predicted from Pasquill-Gifford

assuming that the stability is related to Richardson number as discussed by Golder (1972).

3.3 STABLY STRATIFIED BUILDING WAKES

(NUREG/CR-1247) by K. M. Kothari, J. A. Peterka, and R. N. Meroney, 1980.

Abstract

The velocity and temperature wake behind an isolated building placed in a stably stratified turbulent boundary layer was investigated utilizing wind tunnel tests and mathematical analysis. The mean velocity and mean temperature decreases but turbulence intensity and temperature fluctuation intensity increases as a result of the momentum wake, where the momentum wake is essentially the fluid perturbation resulting from foam drag on the building. However, the vortex wake which is associated with circulation produced by the shear flow acting about the structure increases mean velocity and mean temperature, and decreases turbulence intensity and temperature fluctuation intensity along the centerline of the wake.

A wind-tunnel study of the wakes behind six surface-mounted rectangular building models in a stably stratified turbulent boundary layer was performed for wind direction perpendicular to one face of the building. Measurements of mean velocity, mean temperature, turbulence intensity, temperature fluctuation intensity, velocity-temperature correlations, spectra of velocity and temperature were measured at a Reynolds number greater that 2.0×10^4 with and without the buildings in place.

A method for simultaneous measurements of velocity and temperature was developed. Hunt's (1969) theory for momentum and vortex wakes was evaluated. An analytical technique for prediction of temperature field in the wake of a building using the energy equation for turbulent flow was developed. The present theory considers momentum and vortex wake effects to determine the mean temperature in the wake of a building.

It was found that Hunt's theories for momentum and vortex wakes give very good agreement for mean velocity on the centerline in the wake of a building. It was also observed that the vortex wake was persistent and excess velocity was observed in the far wake region. The theory developed for this research for the temperature field shows an excellent agreement for mean temperature in the wake of a building. The excess temperature in the wake of a building increases up to a certain x/H and then decreases. The temperature wake was extremely persistent and even at x/H = 60 behind all the buildings the wake displayed an excess temperature. This is the result of the horseshoe vortex which brings higher temperature fluid from the top of the turbulent boundary layer towards the ground along the centerline of the building. Hence, the horseshoe vortex plays a very important role in determining any scalar quantity distribution, such as temperature, in the wake of a building.

The velocity fluctuation spectra are similar at various x/H locations with and without a building and obey a -5/3 power law behavior in the inertial subrange. The temperature intensity spectra show a -5/3 power law behavior in the inertial subrange for approach flow conditions; however, a spectra of temperature in the wake of a building have approximately a -1 power law behavior in the inertial subrange.

Though refinement is needed, the analytical theory of Hunt (1969) for the mean velocity field and the present analytical theory for the mean temperature field in the wake of a building correlate closely with the measurements taken in the wind tunnel.

Conclusions

The effects of a building on the approach stable turbulent boundary layer were determined utilizing superposition of momentum and vortex wake perturbations models. Several conclusions were drawn during the discussion of the results, and hence, only primary considerations are outlined here.

1. The effects of a momentum-type wake behind a building in a stable turbulent boundary layer are to decrease mean velocity and mean temperature but to increase turbulence intensity and temperature fluctuation intensity. On the other hand, along the centerline of a building, a vortex wake brings higher-momentum, higher-temperature, less-turbulent and less-temperature-fluctuation-intensity fluid from the top of the boundary layer to increase mean velocity and mean temperature and decrease turbulent intensity and temperature-fluctuation intensity. In stable flow trailing vortices were observed to a distance of $x/H = 60$, beyond which measurements were not performed; hence, the total length of the vortex wake was not known.

2. The wake of an isolated structure, in neutral flow, with one face perpendicular to flow, is less extensive. This characteristic makes the wake structure quite different for stable and neutral flow. Thus, in the wake of an isolated building, particularly in stable flow, both momentum and vortex perturbations effects should be taken into consideration.
3. A theory for temperature distribution in the wakes of buildings was developed considering both of these effects. The method to calculate the circulation of horseshoe vortices at $x = 0$ was generalized. With a single free constant, determined from experimental results, the theory predicts the temperature distribution in the far wake ($x \geq 5H$) of an isolated building. The present velocity measurements show good agreement with Hunt's theory for velocity distribution in the wake of a building.
4. The experimental measurements were compared with the neutral flow data of Woo et al. (1976). The decay rates for the velocity field compared very well in both of these experiments; however, the actual magnitude of velocity defect was different.
5. The temperature wake extends much farther than the velocity wake with all the buildings, showing higher temperature in the wake even at $x/H = 60$ than the approach flow temperature distribution. The high temperatures and excess velocities observed in the far wake strongly suggest

that the horseshoe vortices play a very important role in a wake of an isolated building.

6. The approach flow and building wake integral time scale and integral length scale derived from velocity or temperature variations were slightly different. Both these scales were reduced in the wake of the building as compared to approach flow values confirming the results of previous researchers. The velocity fluctuation spectra are approximately the same at various x/H locations, except in the very near wake, with and without a building in place and obey a -5/3 power-law behavior in the inertial subrange. The temperature fluctuation spectra are different in the approach flow and in the wake, with the -5/3 power-law behavior in the inertial subrange observed only for approach flow. The power-law behavior in the inertial subrange for temperature spectra was close to -1 in the wake region.
7. The differential equations governing velocity, temperature and concentrations of pollutants in the wake of a building have significant similarities. The analytical predictions using the technique developed here of temperature distribution, a scalar quantity, shows better agreement than the velocity distribution. Hence, a similar theory for predicting the diffusion of concentration, a scalar quantity, has been considered as discussed in Section 3.4 following.

Published in the Literature as:

Kothari, K. M., J. A. Peterka, and R. N. Meroney, "Perturbation Analysis and Measurements of Building Wakes in a Stably Stratified Turbulent Boundary Layer," Submitted to the Journal of Fluid Mechanics, Fall 1979, 49 pp.

3.4 THE WAKE STRUCTURE BEHIND A MODEL INDUSTRIAL COMPLEX (NUREG/CR-1473) by Kothari, K. M., J. A. Peterka, and R. N. Meroney

Abstract:

This report presents a study of wake behind an industrial complex deeply immersed in a neutral turbulent boundary layer. The aim of the study was to analyze the wake behavior between idealized model building and the actual industrial complex.

1:200 scale models of the EOCR reactor building and surrounding silo and tank buildings at the Idaho National Engineering Laboratory, Idaho Falls, Idaho, were examined in the Industrial Aerodynamic Wind Tunnel at Colorado State University. The turbulent diffusion around the same complex is presented in the technical report by Hatcher et al. (1977), (NUREG/CR-0373).

It was thought that with surrounding buildings the horseshoe vortices due to the main EOCR reactor building will degenerate. Therefore, the wake structure and diffusion behind the EOCR complex was discussed in light of the momentum wake theory.

Conclusions:

1. The effects of a momentum-type wake behind a complex in a neutral boundary layer are to decrease mean velocity

and increase turbulence intensity. The complex geometry breaks down the horseshoe vortices; hence, one concludes that they should not play important roles in determining the wake characteristics. The wake was detected at a distance of x/H = 35 at a 5 percent mean velocity defect level (or out to 100H at the 1 percent level). Such long wake regions are associated with the low roughness characteristics of the site modeled in the wind tunnel.

2. The present experimental results were compared with the wake theory of Kothari et al. (1980, NUREG/CR-1247) and found to have satisfactory agreement for vertical profiles of velocity defect for all y/H measured except y/H equal to -0.67. The maximum velocity defect rates compared very well with the theory except for y/H equal to -0.67. At y/H = -0.67, the theoretical prediction of velocity defect is less than the experimental measurement. This could be due to the additional velocity defect created by silo and tank buildings. Thus, it can be concluded that the theory predicts the mean velocity defect satisfactory for close to the wake centerline and under-predicts the defect away from the centerline for the complex geometry. The experimental measurements of the decay rates of turbulence excess variance were found to compare very well with that predicted by the wake theory for all y/H locations.

The theoretical prediction of the ground level concentration was compared against the experimental measurements for building and stack height releases. The comparison between the measurements and analytical prediction is very good between x/H = 5.0 to x/H = 35.0. However, for the stack height releases the theoretical predication is higher than the measurements near the building. This could be the result of partial entrainment of the plume by building structures.

3.5 AN ALGORITHM TO ESTIMATE FIELD CONCENTRATIONS UNDER NONSTEADY METEOROLOGICAL CONDITIONS FROM WIND TUNNEL EXPERIMENTS

(NUREG/CR-1474) by Bouwmeester, R. J. B., K. M. Kothari, and R. N. Meroney.

Abstract:

Highest concentrations at ground level are often produced from surface sources with stable atmospheric conditions and near calm erratic winds. This report describes a weighted data methodology developed to predict surface concentrations from stationary wind tunnel measurements and actual meteorological wind fields. Field measurements made downwind of the Rancho Seco Nuclear Power Station (Start et al. 1977) have been compared against a set of wind tunnel measurements around a 1:500 scale model of the same facilities. The algorithm developed in this report has been incorporated into computer program RANSEC to predict hour average concentrations as measured at the Rancho Seco Nuclear Power Station. Wind-tunnel measurements of concentration fields downwind of a 1:500 scale model of the Rancho Seco facility were combined with 2-minute interval meteorological records taken during the field tests to produce a series of synthesized one-hour average concentration data. The weighted data algorithm was realistic in both predicting centerline concentration values as well as the horizontal spread of the plume.

1. This model shows considerable improvement over direct comparison of one-hour average field data to ten-minute equivalert laboratory measurements. The weighting algorithm is generally more realistic in predicting centerline values as well as the horizontal spread of the plume. The weighted average method is generally conservative as compared with the field data.
2. There are some marked dissimilarities between the wind tunnel synthesized and measured field values. At a number of bearing angles the measured values drop suddenly to zero. The synthesized plumes are generally smoother, displaying a monotonically increasing magnitude to a maximum followed by a monotonically decreasing variation to zero.

3.6 SIMULATION OF FUMIGATION IN A WIND TUNNEL

When air follows a trajectory over a cold water surface, the lower layers of the atmosphere are cooled and an inversion develops to a depth of from 100 to 1000 ft. During an onshore wind this stable marine air layer is heated from below by the land surface--assuming a neutral superadiabatic lapse rate in the lower levels while retaining a stable condition above. With increased distance from the shoreline the heated region, or mixed layer, grows vertically until the original stable layer is destroyed. If a tall stack associated with a power plant that is located near the shoreline discharges into the elevated stable layer, the plume initially disperses slowly as it moves downwind. At some point inland the mixing layer extends upward to the plume level. At this point material in the plume mixes rapidly downwind to cause "fumigation" and high concentrations at ground level (Barrett, 1973; Lyons, 1970, 1971, 1973a; Collins, 1971; Van der Hoven, 1967; Smith, 1963). The determination of the spatial extend of the diffusion transition zone becomes an important aspect of the environmental evaluation of industry, fossil-fuel power plants, and nuclear reactors located at coastlines.

A sudden change in the underlying surface over which air flows can induce significant changes in the mechanical and thermal turbulence of the flow, and, consequently, significant changes in the diffusion rates of the atmosphere. When the underlying surface changes from water-to-land or vice versa one confronts local circulation driven by temperature differences commonly called, "sea, lake or land breezes." Although a sea breeze is quite a familiar phenomena, very few detailed low level data are available. This is partially due to the difficulty of measurements over the sea; moreover, it is not easy to distinguish the breeze from superimposed large scale motions.

Sea breezes or lake breezes are accompanied by turbulent transition-zone fumigations. The transition region begins at the shoreline and has the form of a wedge in which the turbulent air slopes upward with distance inland. At the point where the top of this wedge intersects an elevated plume, the contents of the plume will be mixed downward, becoming distributed between the plume and the ground. Van der Hoven (1967), Collins (1971), and Lyons and Olsson (1973) have examined dispersion near coasts. Lyons and Dooley (1974) examined the fumigation of sulfur oxides from the Waukegan, Illinois, power plant. Observations of turbulent transition zones have been made at Big Rock Point Nuclear Plant (Hewson et al. 1963) on Lake Michigan, Millstone Nuclear Power Station (Northeast Utilities, 1965) in Connecticut on Long Island Sound, and Humbolt Bay Power Plant (Robinson et al. 1965) in California.

Dimensional analysis techniques suggest that if the pertinent variables required to describe mixing layer growth are

$$f(x, H, V_a, \Delta\theta, g, T, \Delta T, \delta) = 0$$

where new variables listed are

T = absolute temperature

ΔT = land-water difference

δ = characteristic height over which $\Delta\theta$ and V_a vary upstream

$x(m)$ = distance overland

$H(m)$ = height of mixed layer

$V_a(m/sec)$ = mean velocity

$\Delta\theta(°C)$ = overwater vertical difference in potential temperature within inversion layer.

Then appropriate dimensionless parameters might be

$$\frac{H}{\delta} = f\left(\frac{x}{\delta}, \frac{\Delta T}{\Delta\theta}, g\,\frac{\Delta\theta\,\delta}{T\,V_a^2}, \frac{V_a}{(g\delta)^{1/2}}\right)$$

$$= f\left(\frac{x}{\delta}, HR, Ri_B, Fr_\delta\right).$$

A survey was made of available meteorological data which typified "sea breeze-fumigation" situations in the Great Lakes area (Lyons and Cole (1971), Lyons (1970, 1973a,b). Only two of four experimental realizations appeared complete enough to estimate the required parameters Ri_B and HR. It would appear the laboratory values to examine are

$$(HR)_p = 1.3 \sim 1.9$$

$$(Ri_{Bulk})_p = 1.25 \sim 1.5 \text{ at } H \sim 400'.$$

Laboratory conditions should be chosen to simulate these situations as closely as possible.

The use of a wind-tunnel for model tests of gas diffusion by the atmosphere is based upon the concept that nondimensional concentration coefficients will be the same at contiguous points in the model and the prototype and will not be a function of the length scale ratio. Concentration coefficients will only be independent of scale if the wind-tunnel boundary layer is made similar to the atmospheric boundary layer by satisfying certain similarity criteria. These criteria are obtained by inspectional analysis of physical statements for conservation of mass, momentum and energy. Detailed discussions have been given by Halitsky (1963), Martin (1965), and Cermak et al. (1966). Basically the model laws may be divided into requirements for geometric, dynamic, thermal, and kinematic similarity. In addition, similarity of upwind flow characteristics and ground boundary layer conditions must be achieved.

To summarize the following scaling criteria should be applied for the onshore breeze situations.:

1/ $\mathrm{Re} = \dfrac{\rho_a V_a H}{\mu_a} > 11{,}000$

2/ $\mathrm{Fr} = \dfrac{\rho_a V_a^2}{\Delta\gamma\, D}$; $(\mathrm{Fr})_m = (\mathrm{Fr})_p$

3/ $R = \dfrac{V_s}{V_a}$; $R_m = R_p$

4/ $(z_o)_m = (z_o)_p$

5/ Similar velocity and turbulence profiles upwind

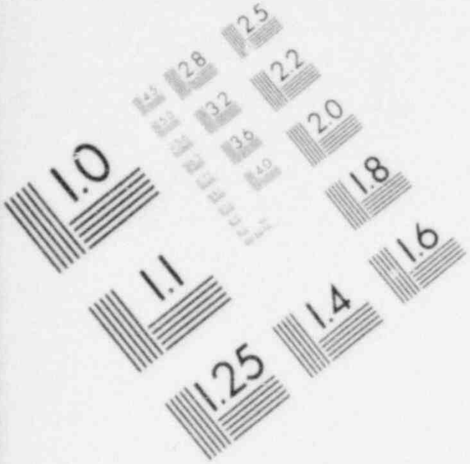
6/ HR = 1.3 ~ 1.9

7/ $\mathrm{Ri}_B = 1.25 \sim 1.5$

It evidently is necessary to obtain a velocity ranging from 4 to 15 cm/sec, and a temperature gradient of 0.5°C/cm to 1.5°C/cm, in order to simulate atmospheric sea breeze phenomena and heated island problems in a wind tunnel facility. The above requirements are equivalent to attaining a Froude number based on the wind tunnel height (60 cm) from 0.030 to 0.196.

3.7 BUILDING WAKE INTERACTION EFFECTS ON PLUME DISPERSION

Previous measurements on the character and persistence of wake regions behind large reactor size buildings have emphasized specific prototype reactor complexes or idealized isolated geometries in the medium to far wake region (i.e., $x > 5H$). A preliminary study was performed to permit estimation of building surface



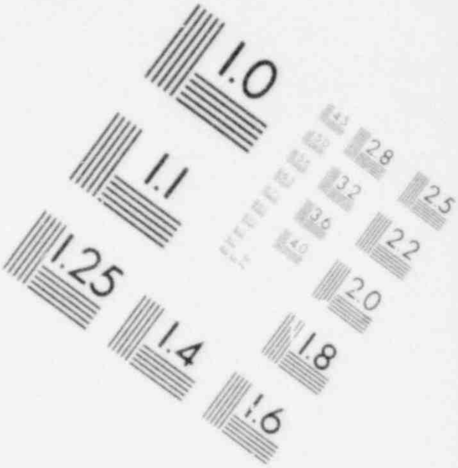
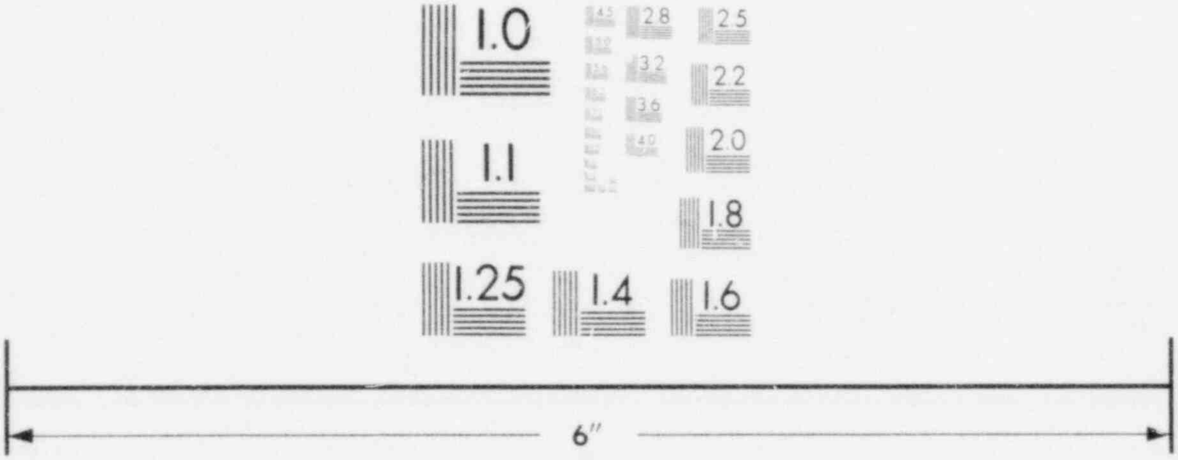
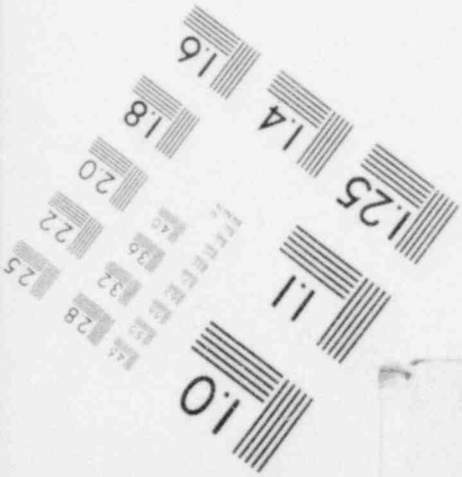
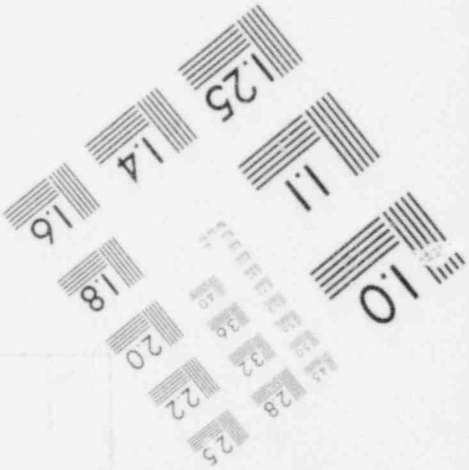


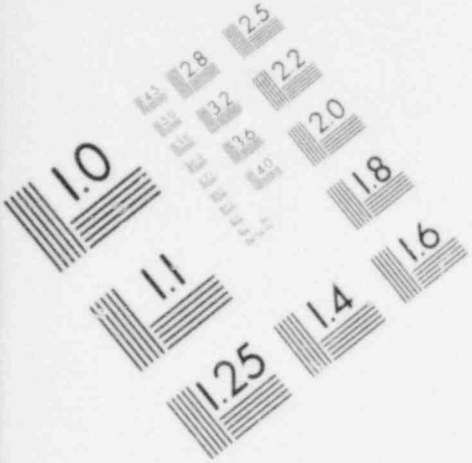
IMAGE EVALUATION TEST TARGET (MT-3)



MICROCOPY RESOLUTION TEST CHART







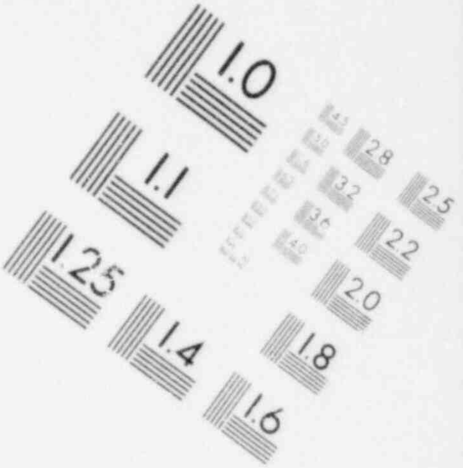
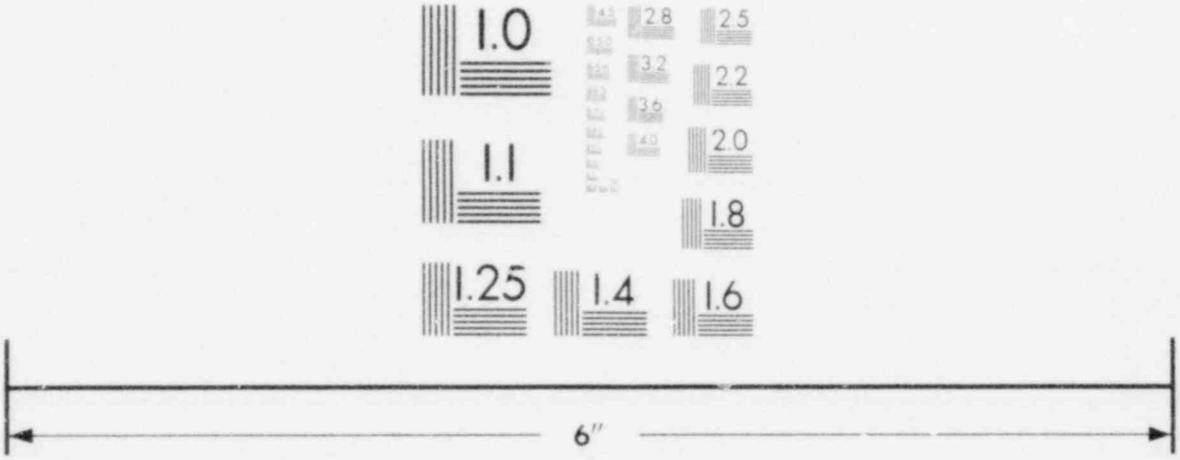


IMAGE EVALUATION TEST TARGET (MT-3)



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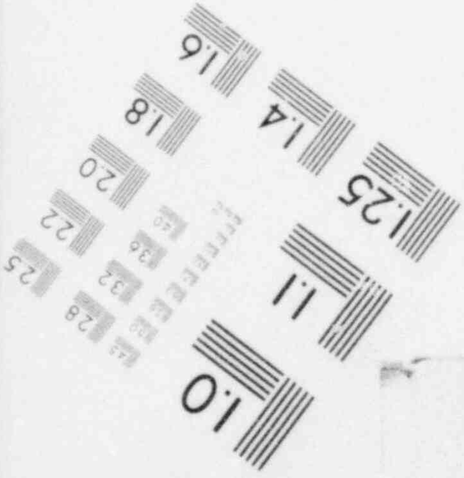

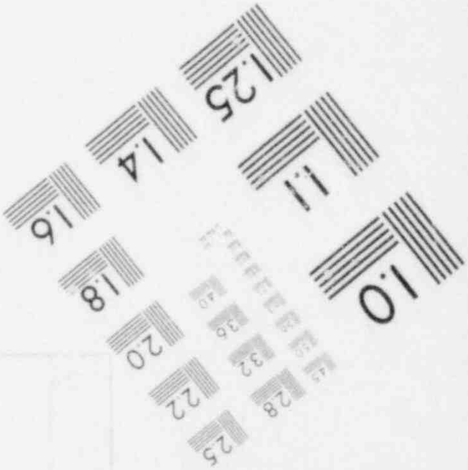

concentrations and resident time of effluent, released into the cavity of the primary or nearby structures.

3.7.1 Experiment

Idealized cubical building models, 15 x 15 x 15 cm, were made out of plexiglas and were deeply submerged in a smooth floor neutral turbulent boundary layer of the Industrial Wind Tunnel at Colorado State University. Effluents were emitted from three locations along the centerline of the upwind release building: half the height of the building on the downwind face, top center of the building, and a stack 1.5 the height of the building at the building center. The measurements of concentration distribution were made on the center of all five faces of the downwind receiving building. The locations of the receiving building with respect to the fixed building are shown in Table 2. Smoke visualization, from the top, was performed for nine positions and three release heights.

3.7.2 Results

The concentration coefficients are reported in a normalized form in Figure 1. This concentration coefficient is determined from $C\overline{U}(H)\ H^2/C_{source}Q_{source})$, where C is concentration (ppm), $\overline{U}(H)$ is the velocity at the building height (m/sec), H is the height of building (m), C_{source} is the source strength (ppm), and Q_{source} is the flow rate (m^3/sec). The initial results of concentration coefficients were plotted against $y_{separation}/H$ for five tap locations and shown in Figure 1 for $x_{separation}/H$ equal to 2.0. The downwind face of the downwind buildings had higher concentrations than the upwind side for all values of y. This effect was clearly noticeable in the flow visualization study. In the recirculating zone of the upwind building, the effluents were lifted upward and out of the cavity region through the shear layer resulting in lower concentrations on the front face of the downwind building. The effluents were trapped in the shear layer of the downwind building and brought towards the ground resulting in higher concentration on rear face of downwind building. It was also observed that for all five tap locations, the concentration coefficient increased up to a certain $y_{separation}/H$ location and then decreased.

3.8 NEAR WAKE DISPERSION BEHAVIOR

An increase in vent stack height and vertical exit velocity are usually expected to reduce effluent concentrations. For most applications the vent gas plume may be considered in a transitional rise state at all locations over a building roof. Some plume rise formulae suggest no increase in effective stack height until the exhaust velocity to approach velocity ratio, w_o/u, exceeds some critical value. Wilson (1976) and Meroney and Yang (1971) found lower surface concentrations may occur even for w_o/u as low as 0.2. Vent velocity ratios of one may reduce maximum receptor concentrations four to five fold. For large vent velocities the plume may penetrate the building separation streamline and considerably reduce receptor concentrations. Fan power to produce such velocities is proportional to the cube of vent gas velocity; hence if large exit velocities are required it may be more attractive to increase vent height itself.

TABLE 2

BUILDING SEPARATION DISTANCE

LOCATION	$x_{separation}/H$	$y_{separation}/H$
1	2.0	0.0
2	2.0	0.17
3	2.0	0.35
4	2.0	0.53
5	2.0	1.15
6	2.0	2.0
7	3.0	0.0
8	3.0	0.26
9	3.0	0.53
10	3.0	0.81
11	3.0	1.73
12	5.0	0.0
13	5.0	0.44
14	5.0	0.88
15	5.0	1.34
16	10.0	0.0
17	10.0	0.87
18	10.0	1.76
19	10.0	2.68

A → Downwind face of the building release

B → Top of the building release

C → 1.5 height of the building release

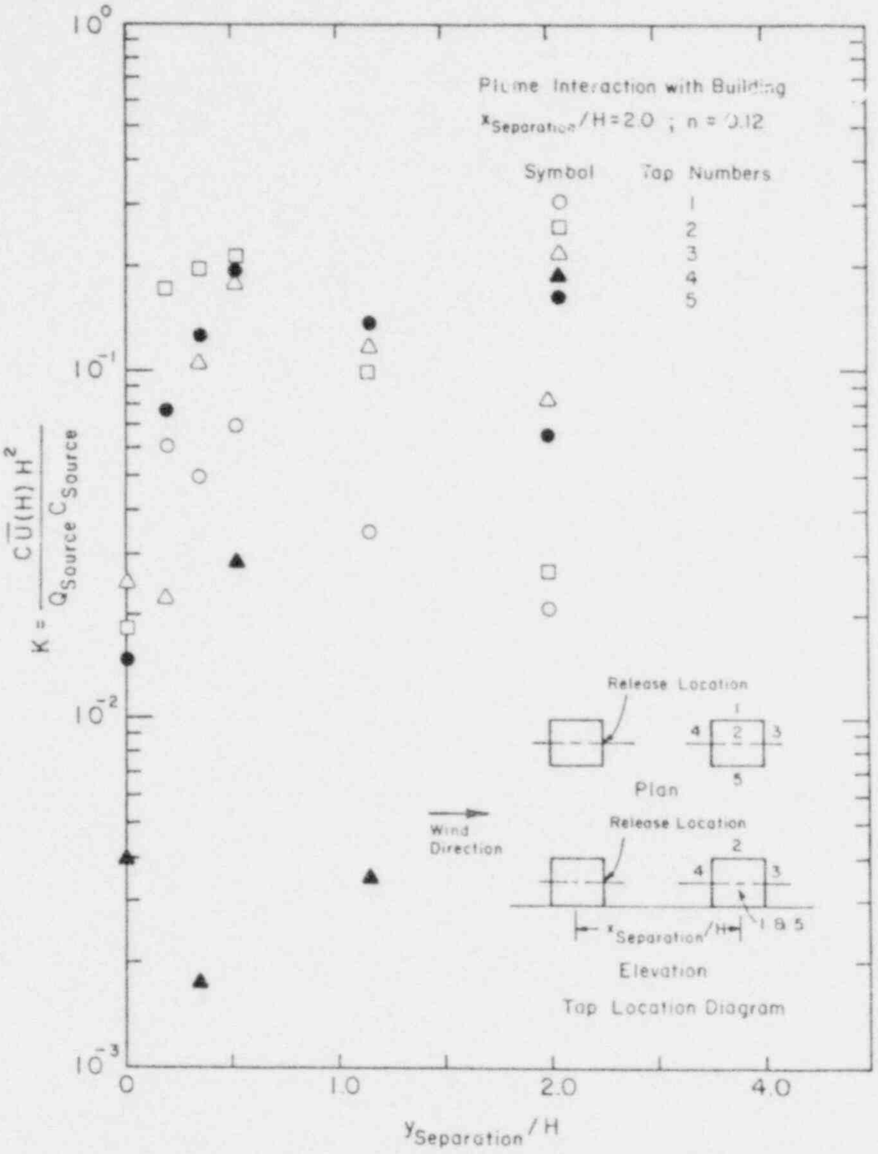

Figure 1. Lateral Profiles of Concentration Measurements on the Downwind Faces of the Building

Probably the most accurate means to estimate intake contamination from roof vents is to produce K isopleth curves for each case by physical simulation. In the event such an exercise is not economically justifiable or convenient, dilution factors may be estimated from a number of formulae developed from the wind tunnel data discussed above. Several authors have suggested the following function for estimating dilution:

$$D' = D \frac{w_o A_o}{UA} = B_1 \left(\frac{S}{\sqrt{A}}\right)^2$$

where D is the ratio of vent concentration, C_o, to local concentration, C and s is the distance from vent to intake found by stretching the shortest possible string between the two points. Halitsky (1962) proposed a constant $B_1 = 0.022$ which underpredicts most dilution by 2 to 5. Wilson's (1976) value of $B_1 = 0.11$ appears to be an accurate lower bound since 99% of the recent measurements around two nuclear reactor facilities correlated by Sagendorf et al. (1979) lie above this line.

Based on Halitsky's Clinical Center test ASHRAE (1974) adopted the following formulae:

$$D' = B_2^2 \left(\frac{S}{\sqrt{A}}\right)^2 + 2B_2 C \left(\frac{S}{\sqrt{A}}\right)\left(\frac{A_o}{A}\right)^{0.5} + C^2 \frac{A_o}{A}$$

where $B_2 = 0.147$ and $C = 4.66$. This formula tends to over-predict dilution near the source. On the other hand, Halitsky's data included measurements above the building surface where concentrations are often higher than the surface itself. The above formulae are displayed together in Figure 2. Halitsky's (1963) curve provides about an order of magnitude factor of safety; whereas Wilson's (1976) curve should provide a lower bound to 99% of all measurements.

Any improvement in approach to the near wake dispersion behavior must depend on a more comprehensive set of dispersion data and a physical model to describe the flow in the near vicinity of structures immersed in shear layers.

A preliminary set of mean and instantaneous concentration measurements have been made in the near vicinity of a simple cubical building; a vent release of the roof center was the source release point.

3.8.1 Experiment

The concentration measurements have been made in the near wake region of a cubical model building. The effluents were emitted from the downwind side of the building and from the top of the building surface. The measurements of concentration distribution were performed for various z/H and y/H distances with x/H locations of 1.0, 2.0, 3.0, and 5.0. The surface concentration of the building faces were also measured. The near wake instantaneous concentration distribution was measured using a new hot-film katherometer technique developed at Colorado State University. The measurements of instantaneous concentration distribution were used to calculate probability distribution functions in the wake of the building and will eventually be compared against the mean concentration

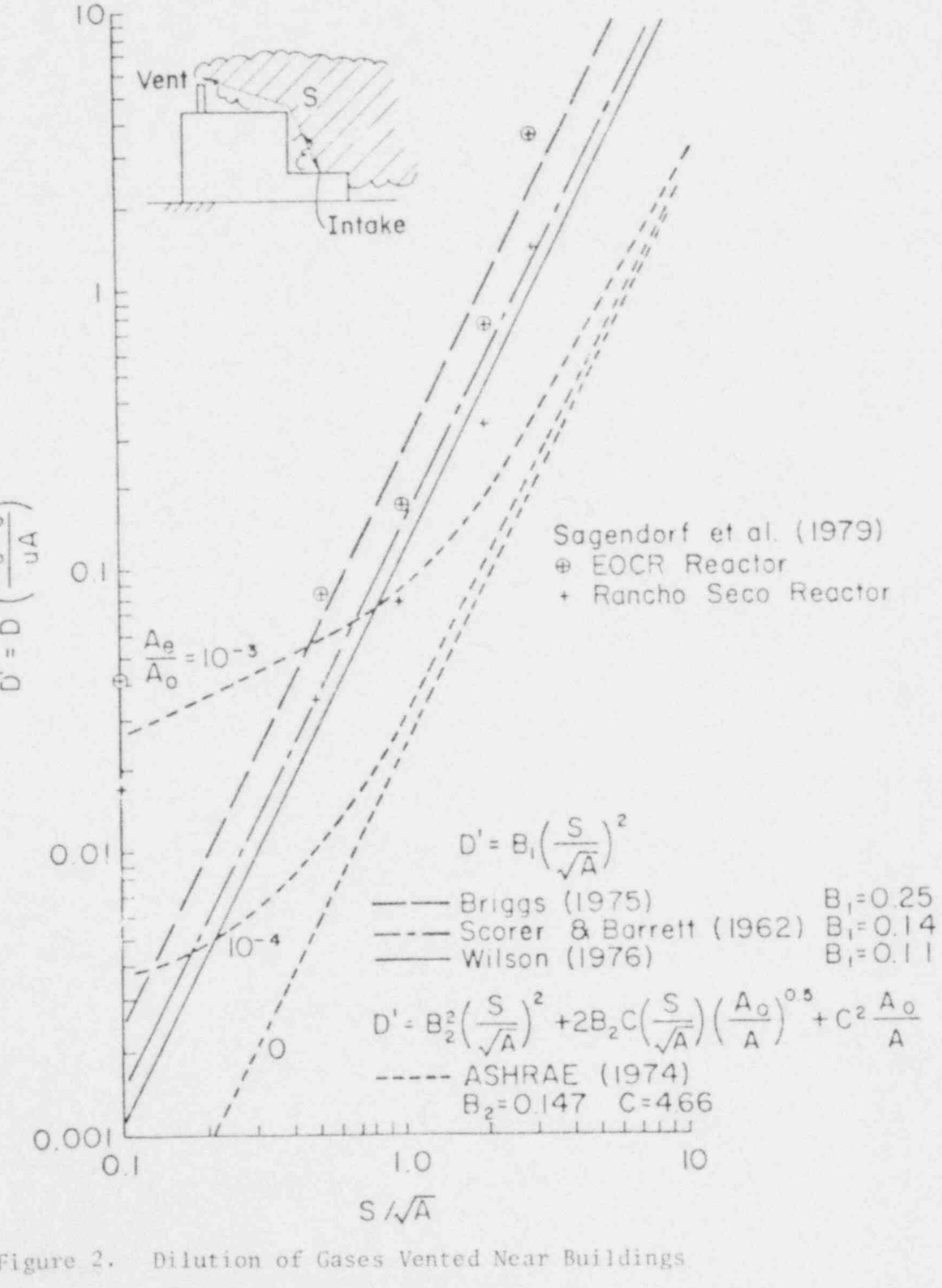

Figure 2. Dilution of Gases Vented Near Buildings

measurement in the wake of a building using a gas chromatograph technique. The flow visualization in the near wake region was performed using a hydrogen bubble technique to investigate Lagrangian dispersion coefficients.

3.8.2 Results

Since low velocity gas release from a flush vent appears to represent a worst case condition for plume dilution, it is instructive to see how building geometry, orientation, and source location influence surface concentration coefficient, K, contours. Side wall concentrations for three roof top vent locations in a typical shear layer are displayed on Figure 3. Isopleths joining points of constant K are shown in each sketch. Except at points very near the vent, the values of K will be independent of K_o at vent exit. Since contour lines are continuous around building edges, it would appear that an intake vent location which cannot "see" the roof vent has no particular advantage over one "on-line-of-sight" the same distance away.

Halitsky performed dilution measurements about rectangular prismatic shapes in a low turbulence uniform velocity field. Since that time few measurements have been reported in the immediate downwind cross-section regions of prototype or model buildings. Figure 4 displays typical recent K-isopleths for a roof vent measured downwind of a cube in a simulated atmospheric surface layer. One notes, that where K is of the order one in the near wake ($x \leq 5H$), spatial variations occur over the cavity region of one order of magnitude.

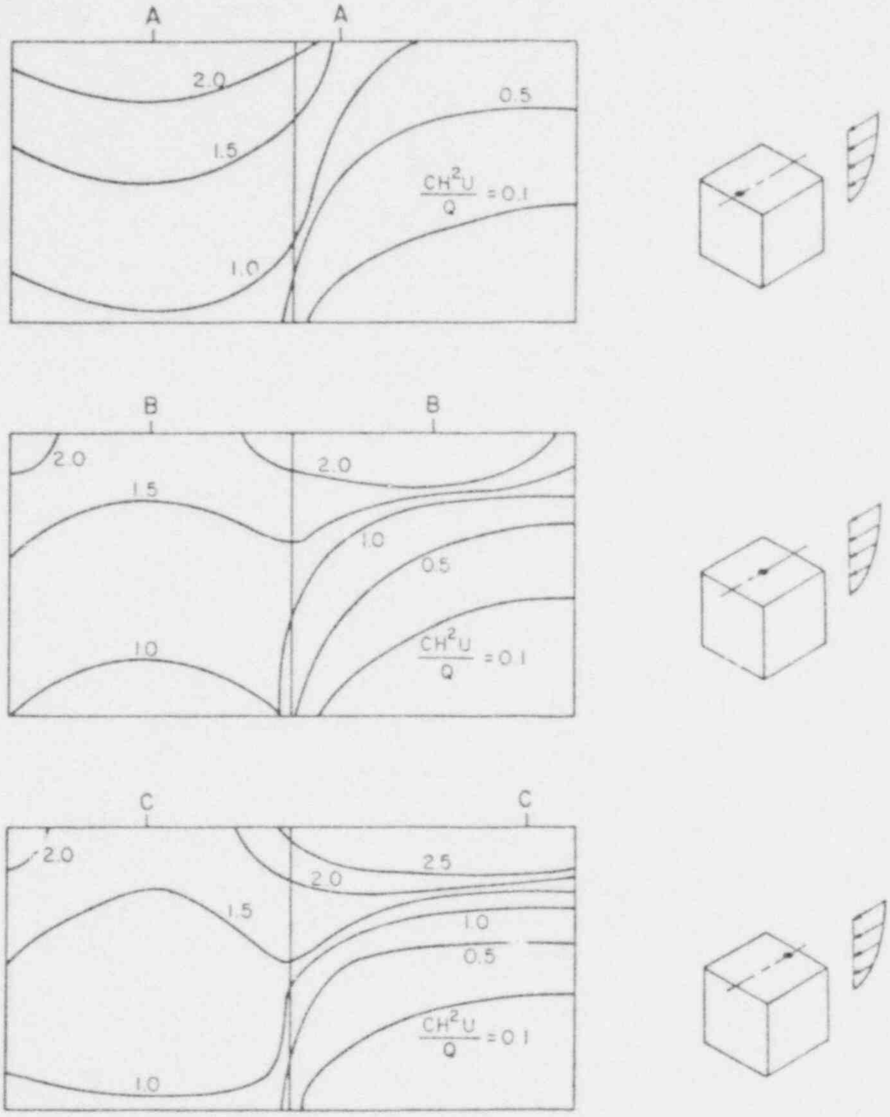

Figure 3. Model Building Surface Concentrations for Various Rooftop Release Locations

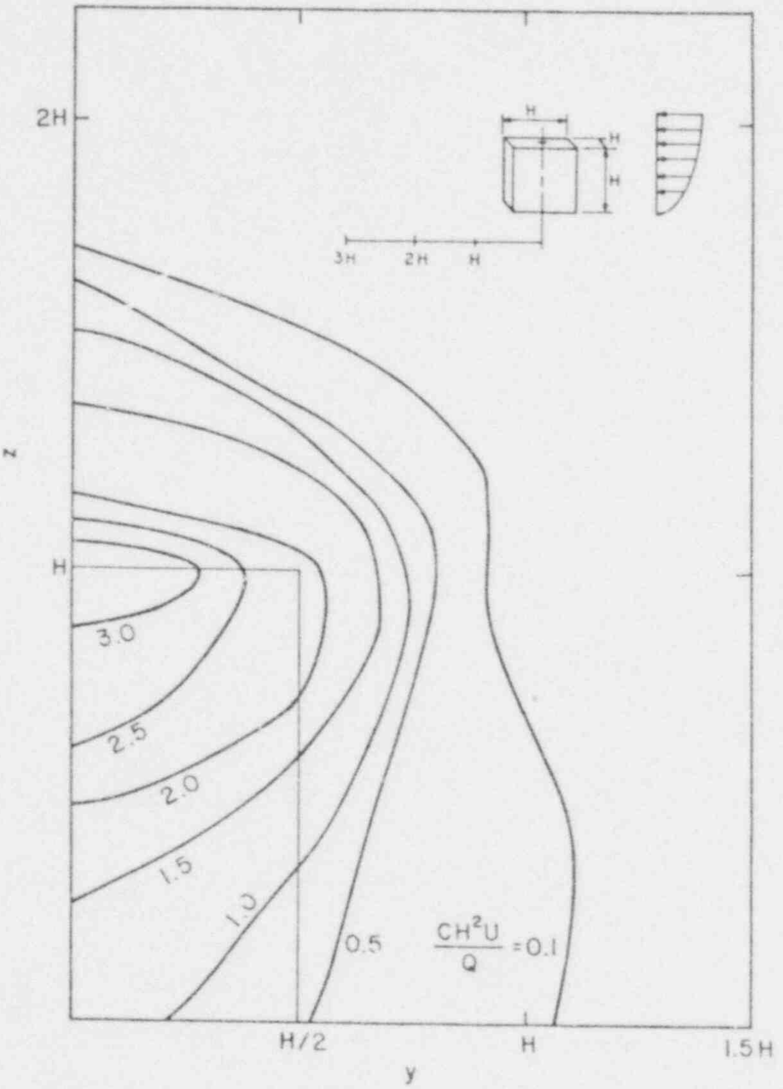

Figure 4. Concentration Contours Downwind of a Model Building Venting Gas From a Short Roof Stack

4.0 SUMMARY

Between 1975 and 1979 via contracts between the Nuclear Regulatory Commission and Colorado State University (Contract No. AT(49-24-0366 and 0236) staff at Colorado State University have performed a sequence of laboratory experiments to evaluate the influence of nuclear reactor building complexes on dispersion of effluents released into their wakes. This study involved research oriented toward quantifying the wake-dispersion interaction as well as a validation exercise to compare laboratory and field measurements about specific sites.

In 1976 laboratory measurements (Hatcher et al. 1976) were completed about the EOCR complex, Idaho Falls, for comparison with field measurements. This is a simple large building in flat-smooth terrain. In 1977 laboratory measurements were completed about the Rancho Seco Reactor complex, again for comparison with field data. During 1978 Rancho Seco reactor complex wind tunnel model data (Allwine et al. 1978) was compared with field results from Start et al. (1977). An extended comparison of field and laboratory results utilizing a time weighting of model results was reported by Bouwmeester et al. (1980).

In addition, basic measurements of the wake structure of model buildings were obtained to increase knowledge of wake behavior of stably stratified atmospheric flows. A new theory of wake behavior has been constructed. Results have been compared successfully against mean velocity, turbulence intensity and temperature perturbations (Kothari et al. 1979). An extended set of concentration measurements were made to evaluate the theory's ability to predict concentration plume perturbations by building wakes (Kothari et al. 1979b). A set of visualization experiments have been performed with a hydrogen soap bubble technique to evaluate Lagrangian trajectories in building wake regions. Preliminary data has been obtained for concentration fluctuations in the near wake region and two-building wake interaction effect on plume dispersion.

To examine shoreline fumigation in a small stratification wind tunnel, a feasibility study was made. The small tunnel was used to examine buoyant plume trajectories in stably stratified flow over a two-dimensional hill (Weil, 1979).

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Between 1975 and 1979 via contracts between the NRC and Colorado State University a sequence of laboratory experiments have been performed to evaluate the influence of nuclear reactor building complexes on dispersion of effluents released into their wakes. This study involved research directed toward quantifying the wake-dispersion interaction as well as a validation exercise to compare laboratory and field measurements about specific sites.

This report presents the program objectives and summarizes the results of two model/field building dispersion experiments; a comparison of perturbation model predictions to model measurements of velocity deficit, turbulence excess, and temperature or concentration perturbations; an examination of the efficacy of a new aloghrithm used to predict full scale concentrations downwind of buildings in nonstationary wind fields from wind tunnel measurements; preliminary measurements of close in dispersion near obstacles; and behavior of a stratification wind tunnel designed to study coastal atmospheric boundary layer behavior.

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